SAND-CAPPING DEPTH AND SUBSOIL INFLUENCE ON TURFGRASS ESTABLISHMENT, PERFORMANCE, AND IRRIGATION REQUIREMENTS

A Thesis

by

DON WESLEY DYER

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Benjamin Wherley
Co-Chair of Committee,	Kevin McInnes
Committee Members,	Richard White
	Casey Reynolds
Head of Department,	David Baltensperger

August 2017

Major Subject: Agronomy

ABSTRACT

Management of golf course fairways and athletic fields can become especially difficult where fine-textured native soils become degraded due to high sodium levels in irrigation water. The sodium causes the clay particles in the soil to disperse, effectively destroying the soil structure. Common problems that arise in these scenarios include excessive fairway wetness, very slow drainage, poor aeration, and severe compaction of highly trafficked areas, all of which result in poor quality turf. To improve turf surfaces, sand-capping of problem fairways and fields has gained popularity in recent years. No recommendations currently exist for specific depths or particle size distribution of capping sands, and less than optimal depths of sand are often used due to the significant cost of renovation. The recommended depth depends on the physical properties of the sand, environmental conditions, and providing a balance of water to air-filled porosity for optimal turf growing conditions. If a capping depth that is too shallow or too deep is chosen, turf quality can be negatively affected. Our research results indicate the overall turf quality and performance behaved differently as a result of the subsoil used. The sand-cap treatments atop the clay loam subsoil maintained a higher overall quality and health throughout the two growing seasons of the study. Furthermore, we found that the shallower capping depth of 10 cm out-performed the deeper 20 cm capping depth in regards to turf quality and cover which was primarily due to the higher moisture contents maintained near the surface and the ease of root development into the underlying

subsoil. Moisture management of sand-capped areas greatly differs from other construction methods, such as the USGA-design construction. With the information gained from this research, this study may lend insight into the development of recommendations for the physical properties of capping sands and how those properties should differ from those currently used for sand in USGA-design putting greens.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Wherley, co-chair, Dr. McInnes, and my committee members, Dr. White and Dr. Reynolds, for their guidance and support throughout the course of this research. I also wish to extend a special thanks to Jim Thomas and Dr. Fontanier for their support and expertise throughout this research.

I am very appreciative to my friends and colleagues and the Soil and Crop Sciences faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the United States Golf Association for financial support of this research.

Finally, thanks to my mother, father, and sisters for their encouragement and support and to my beautiful wife, Cara, for her patience and love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of committee chair, Dr. Benjamin Wherley, co-chair, Dr. Kevin McInnes, and committee members, Dr. Richard White and Dr. Casey Reynolds of the Department of Soil and Crop Sciences of Texas A&M University.

All work for the thesis was completed by the student, under the advisement of Dr. Benjamin Wherley of the Department of Soil and Crop Science.

Funding Sources

This work was made possible in part by the United States Golf Association under grant number [M1401212]. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Department of Soil and Crop Sciences of Texas A&M University.

NOMENCLATURE

EC	Electrical Conductivity
USGA	United States Golf Association
VWC	Volumetric Water Content
WDPT	Water Drop Penetration Time

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
CONTRIBUTORS AND FUNDING SOURCES	v
NOMENCLATURE	vi
TABLE OF CONTENTS	vii
LIST OF FIGURES	ix
LIST OF TABLES	xii
CHAPTER I INTRODUCTION AND LITERATURE REVIEW	1
Irrigation Water Quality	2
Construction of Sand-Capped Systems	6
CHAPTER II EVALUATING SAND-CAPPING DEPTH AND SUBSOIL INFLUENCE ON TURFGRASS PERFORMANCE AND IRRIGATION REQUIREMENTS	11
Overview	11
Introduction	12
Materials and Methods	14
Results	21
Discussion	59
Summary and Conclusions	63
CHAPTER III EVALUATION OF TEMPORAL AND SPATIAL DYNAMICS OF WATER MOVEMENT IN SAND-CAPPING SYSTEMS	65
Overview	65
Introduction	66

Materials and Methods 68
Results 71
Discussion 85
Summary and Conclusions 86

CHAPTER IV SUMMARY AND CONCLUSIONS 88

REFERENCES 90

LIST OF FIGURES

FIGURE		Page
2.1	Percent green cover during establishment as affected by capping depth on the sandy loam subsoil	27
2.2	Percent green cover during establishment as affected by capping depth on the clay loam subsoil	28
2.3	Volumetric water content 0 to 5 cm during establishment as affected by capping depth on the sandy loam subsoil	29
2.4	Volumetric water content 0 to 5 cm during establishment as affected by capping depth on the clay loam subsoil	30
2.5	Percent green cover affected by irrigation frequencies on the sandy loam subsoil for the 2015 and 2016 seasons	32
2.6	Percent green cover as affected by capping depth on the sandy loam subsoil for the 2015 and 2016 seasons	33
2.7	Percent green cover as affected by capping depth on the clay loam subsoil for the 2015 and 2016 seasons	34
2.8	Turf quality as affected by capping depth on the sandy loam subsoil for the 2015 and 2016 seasons	36
2.9	Turf quality as affected by capping depth on the clay loam subsoil for the 2015 and 2016 seasons	37
2.10	Volumetric water content within the 0 to 5 cm sand-cap depth as affected by capping depth on the sandy loam subsoil during 2015 and 2016 seasons	41
2.11	Volumetric water content within the 0 to 5 cm sand-cap depth as affected by capping depth on the clay loam subsoil during 2015 and 2016 seasons	42
2.12	Total root length within the sand-cap as affected by capping depth on the sandy loam subsoil for years 1 and 2	45

2.13 Total root length within the sandy loam subsoil as affected by capping depth 46

2.14 Total root length within the sand-cap on the clay loam subsoil as affected by capping depth 47

2.15 Total root length within in the clay loam subsoil as affected by capping depth 48

2.16 Root mass within the sandy loam subsoil as affected by capping depth.... 51

2.17 Root mass within the sand-cap atop the clay loam subsoil as affected by capping depth 52

2.18 Root mass within the clay loam subsoil as affected by capping depth 53

2.19 Sodium adsorption ratio within the 0 to 2.5 cm depth of the sandy loam subsoil as affected by capping depth........ 55

2.20 Effect of capping depth by date on sodium adsorption ratio within the 0 to 5 cm depth of clay loam subsoil........ 55

2.21 Organic matter accumulation within the upper 0 to 2.5 cm depth of sand-cap as affected by capping depth on the sandy loam subsoil 58

3.1 Fraction finer than a given diameter for a typical USGA root zone mixture and for the capping sand 75

3.2 Moisture release curve depicting the relationship of matric water potential and water content for the sand-capping root zone mixture 77

3.3 Graphic representation of the relationship of the amount of water stored in the sand-cap by the matric water potential at the bottom of the sand-cap root zone........ 78

3.4 Matric water potential at the bottom of the sand-cap root zone as affected by time after irrigation on the sandy loam, clay loam, and gravel layer treatments 80

3.5 Volumetric water content in the 10 cm sand-cap on the sandy loam subsoil as affected by time after irrigation 81

3.6 Volumetric water content in the 20 cm sand-cap on the sandy loam subsoil as affected by time after irrigation 82

3.7 Volumetric water content in the 10 cm sand-cap on the clay loam subsoil as affected by time after irrigation 83

3.8 Volumetric water content in the 20 cm sand-cap on the clay loam subsoil as affected by time after irrigation. 84

LIST OF TABLES

TABLE		Page
2.1	Weather data for the 2014/2015 establishment period as well as years 1 and 2 of the study	22
2.2	Analysis of variance for measured parameters for the fine sandy loam subsoil study	23
2.3	Analysis of variance for measured parameters for the clay loam subsoil study	25
2.4	Volumetric water content as affected by irrigation frequency for the 0 to 5 cm sand-cap depth on the sandy loam subsoil for the 2015 and 2016 seasons	40
2.5	Volumetric water content as affected by irrigation frequency for the 0 to 10 cm sand-cap depth on the clay loam subsoil for the 2015 and 2016 seasons	43
2.6	Root mass within the sand-cap atop the sandy loam subsoil as affected by capping depth for years 1 and 2	50
2.7	Root mass within the clay loam subsoil as affected by irrigation frequency for years 1 and 2	53
2.8	Year 2 electrical conductivity at the 2.5 cm depth of sand-cap as affected by capping depth on the sandy loam subsoil	57
2.9	Year 2 electrical conductivity at the 2.5 cm depth of sand-cap as affected by capping depth on the clay loam subsoil	57
2.10	WDPT within the 1.3 cm depth on the sandy loam as affected by capping depth	59
3.1	Physical properties of the sand-capping material	72
3.2	Particle size analysis report for texture and chemical analysis of the sand-capping material	73

3.3 Sieve analysis of the sand in capping material
(40 g/kg was silt and clay <0.05 mm) 74

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The golf industry continues to grow. In the U.S., the game is now enjoyed by over 20 million players on nearly 16 thousand courses. The industry creates more than 480,000 thousand jobs and its impact on the U.S. economy is estimated to be $32.2 billion per year (Haydu et al., 2008). As the game progresses, there is continuous demand for improvements in course management for playability and quality. The United States Golf Association (USGA) recognizes this, and has contributed more than 40 million dollars towards research projects since 1920 (USGA.org).

There are a number of issues that golf course managers face on a daily basis, but maintaining high quality turf on areas such as fairways, especially when irrigated with poor water quality, may be one of the most challenging. To address this issue, sand-capping, also known as plating, has gained popularity among many golf courses across the United States. Sand-capping is the addition of a layer of sand atop the existing soil. The thickness of the layer of sand varies. Sand-capping is not a new concept, becoming popular over 20 years ago when improved turfgrass quality and conditions were observed from heavy fairway topdressing programs in the Pacific Northwest (White, 2013).

Sand-capped fairways have many advantages including both improved playability and maintenance. A sand-capped playing surface is generally more consistent, firm when wet, and resistant to compaction than to native soil surface.

Interruption for the golf course after heavy rains can be reduced because of its rapid drainage capability. Sand-capped fairways may also eliminate various problems associated with growing turf in poor soils as well as create a more conducive growing medium for turf grow-in and recovery. Cultural maintenance (i.e. irrigation, nutrient, and mowing management) of sand-capped systems is made much easier for the turf manager due to the consistency and uniformity that results from location to location on the course (Robichaud and Banfield, 2006).

Irrigation Water Quality

The quality of water used for turf irrigation on golf courses also has a major impact on long-term turf health and performance. An increase in reclaimed water (wastewater) use has occurred in recent decades on golf courses nationally. This is especially true in populated areas, due to competition for and rising costs of potable water and decline in groundwater quality. Currently, across both the southeastern and southwestern regions of the United States, reclaimed water represents the most widely used water source for irrigating golf course turf, representing 35% of total irrigation water sources used in both regions (GCSAA, 2015).

Reclaimed water generally contains elevated levels of salts, sodium, carbonates, bicarbonates, and other materials that can either directly or indirectly affect turf health and performance. With continued reclaimed water use, even the most salt-tolerant turfgrass species may encounter salinity stress due to accumulation salts in soils over time.

High sodium concentrations found in poor irrigation water creates major hazards for turf both directly and indirectly. Directly, sodium can be absorbed by the roots and carried to the leaves where it may accumulate to toxic levels and cause injury. Indirectly, high sodium concentrations can displace favorable cations on the soil cation exchange capacity, thereby causing the soil aggregates or organic matter in the soil to disperse, destroying the soil structure and reducing soil permeability (USGA, 1994). Sodic soil effects may include: the destruction of macropores, a decline in water infiltration (permeability), a decrease in percolation and drainage, an increase in soil hardness, and a decrease in soil oxygen concentrations that lead to anaerobic soil conditions (Carrow and Duncan, 1998). Sodium permeability hazard has traditionally been measured in the soil or irrigation water through calculation of Sodium Adsorption Ratio (SAR), which can be calculated by the following formula:

$$SAR = \frac{Na}{\frac{\sqrt{Ca + Mg}}{2}}$$

In this formula, sodium, calcium, and magnesium concentrations are aqueous concentrations (meq L^{-1}). Based on this relationship, as sodium concentration increases, SAR increases. An SAR greater than nine in irrigation water can lead to lower permeability issues in fine-textured soils. However, in course-textured soils, such as sands, permeability issues are greatly lessened and a SAR of this level can be tolerated. When HCO_3 is >120 mg L^{-1} and CO_3^{-2} is >15 mg L^{-1}, adjusted SAR is recommended to use when assessing sodium hazard of water or soil. Adjusted SAR takes into account the carbonate and bicarbonate levels in solution, which can worsen sodium's effect (Huck et al., 2000).

Another less commonly used method of assessing sodium permeability hazard in a soil is through calculation of exchangeable sodium percentage (ESP), which can be calculated by the following formula:

$$ESP = \frac{Exchangeable\ sodium\ (meq/100\ g)}{Cation\ exchange\ capacity\ (meq/100\ g)} \times\ 100$$

An ESP value greater than 15 has been considered to represent a level of concern. (USGA, 1994)

Salinity stress may also arise when irrigating with reclaimed water. When soluble salts in the root zone become too high, salinity problems can result. Salt affects plants by decreasing available water to plants by the osmotic inhibition of water absorption and will eventually cause roots to wilt and die. Furthermore, it can create nutritional imbalances and mineral toxicities due to the salt ions (USGA, 1994). Salinity of soil solution or irrigation water is most commonly measured as electrical conductivity (EC), but can also be assessed in terms of total dissolved salts (sometimes also referred to as total dissolved solids), or TDS. Reclaimed irrigation water has been reported to contain electrical conductivity ranging from 1-2 dS m^{-1}, but this may become more elevated during periods of low rainfall (Huck et al., 2000). In soils, salts will accumulate near the surface due to evapotranspiration (ET) of water from the turf and soil. In this way, salts may accumulate to higher levels than that originally contained in the irrigation water, especially during periods of high evapotranspiration and low precipitation. Therefore, salt-tolerant species selection and maintenance leaching practices have become a major component of successful agronomic programs for managing salinity (Carrow et al., 2000).

Leaching of salts can be performed much more easily in sands than heavier native soils due to greater macropore space. Therefore, providing a layer of sand through sand-capping, can allow the turf manager to more easily move salts downward below the roots, and thus, minimize salt accumulation in the root zone. This can be performed through use of a maintenance leaching requirement (LR) which estimates the additional amount of irrigation water needed beyond that needed to replace ET for leaching salts through the root zone. In the following formula, EC_W represents the electrical conductivity (EC) of the irrigation water and EC_e is the threshold EC for the turfgrass (Carrow and Duncan, 1998).

$$LR = \frac{EC_W}{5(EC_e) - EC_W}$$

Another important consideration when evaluating suitability of irrigation water or soils for turf growth is concentrations of carbonates and bicarbonates. Bicarbonates effectively worsen sodium’s effects on soil structure by merging with calcium and/or magnesium, causing them to precipitate out of solution as calcium and/or magnesium carbonate and further decreasing soil permeability. Typically, water and soils high in carbonates/bicarbonates are also characterized by elevated pH. Residual sodium carbonate (RSC) levels are one means of assessing the level of carbonates in soil or water, and can be calculated by the following equation:

$$RSC = (HCO_3 + CO_3) - (Ca + Mg)$$

where HCO_3, CO_3, Ca, and Mg are aqueous concentrations (meq L^{-1}).

A residual sodium carbonate (RSC) value of 1.25 meq L^{-1} or less is considered safe, a value of 1.25 to 2.5 is marginal, and a value of 2.5 and greater represents a carbonate/bicarbonate hazard.

Finally, pH of the irrigated water plays a major role in the overall plant's health. Most plants grow optimally in a soil pH of 5.5 to 7.0, but the desirable pH of irrigated water is 6.5 to 8.4, as the majority of essential plant nutrients are highly water-soluble in this range. As previously mentioned, bicarbonates will slowly raise the soil pH to a more alkaline state. Potential element deficiencies, particularly related to micronutrients, tend to result in plants grown in an alkaline pH environment (Harivandi, 2004).

Construction of Sand-Capped Systems

Given the increasing adoption of reclaimed water for irrigation of golf courses and athletic fields worldwide and the negative effects this creates on heavy native soils, the process of sand-capping has gained in popularity, both at initial construction but also during renovation of golf course fairways and athletic fields. Construction of sand-capped systems first involves removing and stockpiling any existing fairway topsoil for use in shaping contours throughout the golf course. Fairways are then shaped and rough-graded using the subsoil, with subsurface drains installed at suitable intervals for removal of excess water. Then, the entire fairway is covered with a uniform layer of sand. In theory, the ideal depth of the sand layer recommended by soil physical testing laboratories based on the physical properties (i.e. texture) of the sand used, with the ultimate goal of providing an equal ratio of water to air-filled porosity in the root zone.

However, in practice, many architects and owners commonly use less than ideal depths than that specified, in order to reduce construction cost. For example, some courses will construct a 10 cm sand-cap regardless of the physical properties of the sand (Thomas, 2014). Field observations also reveal that in practice, this layer is commonly spread to depths of less than 5 cm near fairway edges in a process known as “feathering out the edges.” Variable depths of sand-cap construction will ultimately create challenges for golf course superintendents in their attempt to produce consistent soil moisture and fairway turf quality. Also, due to the appreciable cost to sand-cap an existing golf course, some golf courses will spread out the cost over time by gradually building up a layer of sand through a routine topdressing, with thin layers over time (Sayer, 1994). There are pros and cons when taking this approach, however many golf courses in the Pacific Northwest, Florida, Hawaii, and California have had overwhelming success (Gilhuly, 2014).

Field observations also suggest that for many sand-capped systems, the vast majority of turfgrass roots are concentrated in the sand-cap layer, with little to no penetration deeper into the subsoil. Depending on the depth of the sand-cap layer, this could have a considerable influence on the amount of plant-available nutrients and/or water held within the root zone as well as the required frequency of irrigation. Over time, restricted rooting could become an even greater concern if the underlying soil begins to seal off due to buildup of sodium. Given the importance of a deep, non-restricted root zone, this could conceivably impact the turf’s potential to withstand and recover from drought (Stienke et al., 2011 and 2013). Stienke et al. (2005) reported after an imposed 60-day drought period, no turfgrass species survived in a 10 cm deep depth layer of soil over an impermeable plastic barrier (Stienke et al., 2011). The potential for a restricted root zone confined to the sand layer is an important consideration for sand-capped systems because of the increasing need for golf courses to periodically reduce or restrict water to fairways during mandatory water allocation reduction periods (Stienke et al., 2013).

In addition, cultural management considerations for sand-capped systems remain largely unknown. For example, the potential for organic matter accumulation, irrigation requirements, and the potential for developing hydrophobic soils are all aspects that have received very little attention in previous research and should be explored in more detail. It has been suggested that cultural practices such as aerating, grooming, vertical mowing and topdressing may be necessary on sand-capped systems in order to minimize organic matter accumulation. Thatch and organic matter may actually have greater potential for accumulating on sand-capped fairways and tee boxes compared to golf greens due to the higher mowing heights and less frequent thatch programs (White, 2013).

When considering sand for root zone material, knowledge of the physical properties of the sand is crucial (White, 2013), as particle size distribution, particle shape, and bulk density of sand can directly impact health and performance of the turf/soil system. The United States Golf Association (USGA) has developed recommendations for physical properties of sand-based root zones used for putting greens, but sand suitable for greens might not be suitable for sand capping for several reasons. The sand layer on a USGA-design putting green is placed above a coarser gravel layer (USGA, 2004). With proper choice of sand, this type of construction can give ideal growing conditions for turfgrass roots by providing a favorable air and water environment.

The ideal sand depth is determined by its water content-water potential. The particle distribution and bulk density of the sand determines the shape of the curve and will vary among different sands (McIntyre and Jakobsen, 1993). Unfortunately, the USGA currently has no recommendation for a sand-cap system that is placed directly atop a finer-textured soil, and water relations in this type of system will likely behave differently than those of an USGA-design green. For example, the soil water content of the sand-cap may become too dry or remain too wet depending on the depth of sand used. Additionally, the texture of the subsoil onto which the sand-cap layer is placed may influence water relations within the sand-cap, due to variation in infiltration rates and tension differences between soils of various textures.

While the practice of sand-capping is increasing, there is currently limited research-based information and published data regarding the influences of sand-capping depth and subsoil composition on turfgrass performance and management. Areas of importance from an agronomic research standpoint could include1) assessing turf quality, canopy cover, and root distribution as affected by various sand-capping depths and subsoils, 2) evaluating sand-capping and subsoil combinations and their influence on root zone moisture and irrigation frequency requirements, and 3) determining the temporal and spatial dynamics of salts (EC) and monitoring rate of development of subsoil sodicity (SAR) in response to sand-capping x irrigation treatments when managed with irrigation water containing elevated sodium.

CHAPTER II

EVALUATING SAND-CAPPING DEPTH AND SUBSOIL INFLUENCE ON TURFGRASS PERFORMANCE AND IRRIGATION REQUIREMENTS

Overview

Golf courses and sports fields with turfgrass surfaces are moving toward sand-based root zone construction to ensure optimal playability, performance, and longevity. Turf areas where fine-textured native soils become degraded due to elevated concentrations of sodium in irrigation water can become especially difficult. Excess sodium causes clay particles to disperse, effectively destroying the soil structure. Sand-capped systems are ideally suited for this scenario where poor water quality and/or clayey soils necessitate rapid drainage and the need to flush salts. There is limited research-based information regarding the influence of sand-capping depth and subsoil composition on performance of turfgrass systems or cultural management requirements. Our research tested the hypothesis that sand and subsoil characteristics influence dynamics and availability of water as well as subsequent turf canopy characteristics and root development. The objectives of this study were to 1) assess season-long visual turf quality and root distribution of Tifway bermudagrass fairway turf established on various sand-cap depths atop two different subsoils, 2) determine how sand-capping by subsoil combinations influence root zone soil moisture and irrigation frequency requirements (one vs. two day per week irrigation) of bermudagrass fairways, and 3) determine the temporal and spatial dynamics of salts through measurement of electrical conductivity (EC) within the sand-cap and sodium adsorption ratio (SAR) within subsoil. Results show that overall turf quality and performance performed differently among the various capping depths and subsoils used, and playing surfaces can be negatively impacted if the wrong capping depth is chosen in sand-capping construction systems.

Introduction

Sand capping (also known as "plating") of golf course areas is not necessarily a new concept in golf course construction and maintenance, but it has gained popularity in recent years, especially on fairways. The trend has been driven by the need for improved turfgrass growing and playing conditions, especially in areas where poor quality irrigation water and/or fine-textured native soils exist. Given the growing need to conserve potable water resources, golf courses must increasingly be managed using poor quality irrigation water sources. A key example of this is the increasing adoption of reclaimed water for irrigation on U.S. golf courses, which, according to the most recent Golf Course Superintendents Association of America's Environmental Institute of Golf Survey, increased by 33% from 2005 to 2013 (GCSAA, 2015). Reclaimed water may contain elevated concentrations of sodium, salts, bicarbonates, dissolved solids, and other materials that can be detrimental to the health of the turf and/or soil physical properties (United States Golf Association, 1994). If areas receiving poor quality irrigation water are left unmanaged, golf courses and athletic complexes can experience rapid loss of permeability of native soil due to sodium. As a result, renovation and new construction budgets commonly include either aggressive topdressing or sand-capping of turf areas to produce a soil profile that is more conducive to root growth, leaching of salt, and soil moisture management.

Field observations also suggest that for many sand-capped systems, the vast majority of turfgrass roots may be concentrated in the sand-cap layer, with little to no penetration deeper into the subsoil. Depending on the depth of the sand-cap layer, this could have a considerable influence on the amount of plant-available nutrients and/or water held within the root zone as well as irrigation frequency requirements. Over time, restricted rooting could become an even greater concern if the underlying native 'subsoil' begins to seal off due to a buildup of sodium and loss of soil structure. In these scenarios, the turf's ability to withstand and recover during periods of drought could be greatly compromised. For example, Stienke et al. (2005) conducted a 60-day drought study using multiple warm-season grass species and found that no turfgrass species on 10-cm deep soil atop an impermeable plastic sheet survived without water (Stienke et al., 2011).

Sand-capping can also add significant expense to a construction/renovation budget, often exceeding $1 million for an 18-hole golf course. Consequently, less-than-optimal depths of sand are often used (Thomas, 2014). Furthermore, variable depths of sand-cap across a fairway or 'feathering out' sand toward fairway edges can create variability in soil moisture and challenges for golf course superintendents in their attempt to produce consistent soil moisture and fairway turf quality. Due to the major renovation cost to sand-cap, some golf courses will attempt to spread out the cost over time by gradually building up a layer of sand through topdressing (Sayre, 1991).

Although the United States Golf Association (USGA) currently does not offer any recommendation related to depth or particle size distribution of capping sands, physical testing laboratories commonly recommended placement depth based on similar assumptions from which USGA putting green root zones are determined, which is to provide an equal balance of water to air-filled porosity in the sand at field capacity as well as the assumption of 0 cm tension at the sand-subsoil interface (Thomas, 2014). However, the water relations and plant growth in sand over soil (i.e. sand-capped) systems are likely to differ greatly from those where sand is layered atop gravel. Currently, there is limited published agronomic information available to guide development of recommendations for sand-capping.

Therefore, the objectives of this research were to 1) assess season-long visual turf quality, canopy cover, and root distribution of ‘Tifway’ bermudagrass fairway turf constructed to sand-cap depths of either 0 cm/topdressed, 5 cm, 10 cm, or 20 cm atop both fine sandy loam and clay loam subsoils, 2) determine how sand-capping by subsoil combinations influence root zone soil moisture and irrigation frequency requirements (one vs. two day per week irrigation), and 3) determine the temporal and spatial dynamics of salts, as characterized through EC and SAR measurements within the sand-cap and subsoil, as influenced by sand-capping depth, subsoil, and irrigation frequency treatments.

Materials and Methods

Research Site and Plot Construction

This research was conducted at the Texas A&M Turfgrass Field Laboratory, College Station, TX from August 2014 to October 2016. The 0.2 ha sand-cap research facility was constructed along a north-to-south running 1-2% slope. Half of the facility was constructed atop a Boonville fine sandy loam (fine, smectitic, thermic Ruptic-vertic Albaqualf) containing 15% clay, 20% silt, and 65% sand. This native sandy loam soil had a pH 4.9. On the other half of the facility, native soil was excavated to a depth of 30 cm and moved off site before being replaced with a locally sourced clay loam soil containing 38% clay, 35% silt, and 27% sand. This clay loam soil had a pH 7.5. The subsoils were laser graded to produce a final 1.5% east-to-west slope across the facility to facilitate drainage to drainage ditches at the perimeter of the facility.

Atop each of the two subsoils (studies), irrigation frequency (main plots) and sand-cap treatments (sub-plots) were arranged in a split-plot design, with 3 replicate plots per treatment. Irrigation frequency treatments included irrigation supplied at either 1 or 2 times weekly. All plots received irrigation volumes of 0.6 x reference evapotranspiration (ET_o), based on 40-year historical weather data for the location obtained through the Texas ET Network (texaset.tamu.edu). Rainfall amounts were recorded using a rain gauge, and used to adjust irrigation amounts accordingly (Table 2.1). The irrigation water used was the local municipal potable water source, which originated from deep aquifers and was of marginal agronomic quality, due to high levels of sodium bicarbonates (pH 8.1, SAR_{adj} = 23).

A locally sourced, medium-coarse textured sand was used to produce the sand-cap treatment plots, which were constructed to depths of either 0 cm (topdressed to a depth of 2.54 cm per year), 5 cm (shallow), 10 cm (medium), 20 cm (deep). Forms were used to achieve the desired depth, and a mechanical tamper was then used to firm and compact sand to prevent settling during establishment. A moisture barrier (CSP

Outdoors, Shreveport, LA) was then installed around all borders of each plot to a depth of 45 cm in order to prevent lateral movement of water to adjacent plots.

Establishment and Grow-In Phase

The establishment period for the study began in September 2014, with full establishment of plots attained by May 2015. Washed Tifway bermudagrass (*Cynodon dactylon* (L.) Pers. x. *C. transvaalensis* Burt-Davy*)* sprigs were established on plots in September of 2014 at a rate of 2152 bushels ha^{-1}. Sprigs were topdressed, rolled, and irrigated multiple times daily in order to prevent wilt and desiccation. During the establishment phase, plots received 2.45 g N m^{-2} biweekly for the months of September, October, November, March, and April using a complete (13-13-13) fertilizer (American Plant Food Corp., Galena Park, TX). Micronutrients were also supplied regularly during the establishment period using K-Step Hi Mag fertilizer, supplied at a rate of 7 g m^{-2} monthly. During the establishment period, plots were mowed using a reel mower, with the height of cut gradually reduced from 2.5 cm during the fall to 1.3 cm by early spring. By May 2015, all plots had achieved full cover, as confirmed through both visual as well as digital evaluations of % cover. Hereafter, the 2015 season will be referred to as 'year 1', while the 2016 season will be referred to as 'year 2'.

Cultural Management of Established Plots

Once treatment plots had attained full establishment, standard fairway cultural practices were imposed for the duration of the project. As such, irrigation was provided to all plots from May through October at a level of 0.6 x ET_o, applied either once, or split into two applications weekly. Mowing was performed on all plots one to three times weekly at a 1.3 cm height of cut through the growing season, with clippings returned. Verticutting was performed once during the month of July in both years one and two to a cutting depth of 1.3 cm. With the exception of the 0 cm treatment, which was topdressed five times during the growing season to build up a sand layer of 2.54 cm per year, no aeration or topdressing was performed during the study period on any plots. Fertilizer management was kept uniform between all treatments during the study. Nitrogen was applied at a rate of 4.9 g N m^{-2} every six weeks using a 21-7-14 fertilizer (American Plant Food Corp., Galena Park, TX), which contained 25% sulfur urea, from May through September both years. Although initially, we had planned to supply nutrients to plots based on nutrient levels within the 0 to 10 cm sand-cap layer, soil analyses indicated that all nutrients within this layer were well below sufficiency levels due to the inherently low CEC and organic matter available for retention of nutrients in the sand-cap layer. Therefore, soil nutrient levels within the subsoil were used as a basis for achieving fertilization goals. Based on results of 0 to 2.5 cm depth subsoil nutrient analyses performed twice annually during the study, all macro and micronutrients were determined to be at or above sufficiency levels. However, to ensure adequate nutrient availability, plots were fertilized twice annually (May and August) using K Step Hi-Mag fertilizer at a rate of 7 g m^{-2}.

Evaluations of Turf Cover and Quality

Establishment data were collected 8-weeks after sprigging in November 2014 to assess percent green cover in plots. To perform these assessments, a portable light box consisting of 4 compact flourescent 23-watt light bulbs was used to create a uniform light source, and a digital camera (Canon PowerShot SX-170 IS, Tokyo, Japan) was used to record plot images. Images were taken at the center of each plot. Digital images were then analyzed for percent green cover using the SigmaScan Pro (Systat Software, Inc., San Jose, CA) combined with the Turf Analysis v2 macro (Karcher and Richardson, 2003; Karcher and Richardson, 2005). Surface moisture content at the 0 to 5 cm depth was also obtained on the same day using the FieldScout 300 TDR Moisture Meter (Spectrum Technologies, Inc, Aurora, IL).

For assessment of turf quality and canopy cover, plots were evaluated twice monthly from June through September of years 1 and 2, using a visual ratings system for turfgrass quality which utilized a 1-9 scale, with a rating of 5 or greater denoting acceptable quality (adapted from Shearman and Morris, 1998). Digital image analysis of light box images were also taken every two to four weeks during the study and analyzed for determination of percent green cover as described previously.

Evaluation of Root Development

Turf rooting depth and distribution within the soil profile was assessed through root sampling performed in October of both years of the study. A tractor-mounted hydraulic root sampler was used to remove 5 cm diameter cores, both for the entire sand-cap as well as for the 0-30 cm depth within subsoils within all treatments. Samples were then sectioned into sand-cap and subsoil layers before rinsing soil free from roots. Total root length measurements were then obtained by scanning each root sample using WinRhizo software program (Regent Instruments Inc., Ontario, Canada) Following total root length analysis, root samples were oven dried at 65 °C for 72 h before obtaining root dry weights.

Soil Moisture, Electrical Conductivity, and Subsoil Sodium Measurements

Twice monthly from June through September, volumetric water content (%) was determined for each sand-cap treatment using a hand-held field scout TDR 300 soil moisture meter (Spectrum, Inc.,Aurora, IL). Differing sensor probe lengths corresponding to the depth of each sand layer were used in order to determine the average volumetric water content within each sand-cap. Measurements were collected during the afternoon hours prior to irrigation days for both one and two day per week irrigation treatments.

In order to characterize the temporal and dynamics of salt accumulation within the sand-cap, electrical conductivity was also monitored monthly using a handheld EC meter (FieldScout EC 110, Spectrum Technologies, Aurora, IL) within the upper 2.5 cm of the sand-cap in all treatments. For subsoil SAR determination, 0 to 5 cm subsoil samples were obtained during the spring and fall (prior to and after irrigation was imposed each season) of both years from the 2 day per week irrigation treatment. Samples were then submitted to the Texas A&M AgriLife Soil, Plant, and Water Laboratory for SAR and full nutrient analysis.

Organic Matter Accumulation

During the fall at the conclusion of both years 1 and 2, 5 cm diameter core samples were removed from the surface (0 to 5 cm) of sand-cap plots for the fine sandy loam subsoil study for determination of % organic matter. Just prior to sample removal, plots were lightly irrigated in order to ensure integrity of and prevent separation of samples. Immediately after soil/turf core removal, shoot tissue and verdure were removed from each sample using scissors. The remaining thatch/soil layer was then oven-dried at 105 °C for 72 hours to remove all water and immediately weighed. Samples were then transferred into a muffle furnace (Thermolyne, Sybron Corporation) at 550^{o} C for 4.5 hours, and reweighed for determining percent organic matter based on loss on combustion.

Surface Shear Strength Evaluation

In October 2016, shear strength was evaluated for all treatment plots using the shear van apparatus TSHEAR2-M (Turf-Tec International, City, ST). Shear strength provides a measurement of the stability of turfgrass canopy and root system strength and stability. Two hours prior to taking measurements, plots were lightly irrigated with 0.3 cm irrigation in order to provide uniform surface moisture between plots. Plots were also tested for soil moisture prior to shear strength testing in order to ensure consistent moisture contents among treatments. The shear vane foot was used for testing the upper, middle, and lower third of each plot. The 3 readings were then averaged for each treatment plot. Readings are presented in units of Newton meters (N m). Based on manufacturer literature, minimum acceptable strength has been noted to be ≤ 10 Nm, fair strength is noted as 10-15 Nm, good strength is noted as 15-20 Nm, and exceptional strength is noted to be ≥20 Nm (Turf-Tec Shear Strength Tester, 2017. Available at http://www.turf-tec.com/Tshearlit.html).

Sand-Cap Hydrophobicity Testing

Soil water repellency was determined by using the water drop penetration time (WDPT) test (Dekker and Ritsema, 1994). Briefly, three 2.5 cm diameter x 10 cm deep turf/soil samples were removed from each plot, one from the upper, middle, and lower 1/3 of each plot. An eyedropper was then used to place a droplet of distilled water onto the turf/soil core sample at the various depths below the soil surface including the 1.3 cm, 3.8 cm, and 7.5 cm depths. The amount of time (s) required for this water droplet to infiltrate the soil was then recorded. A WDPT threshold of 5 seconds was used to determine if hydrophobicity was present (Bisdom et al., 1993).

Analysis of Data

For determining statistical significance results, data for each parameter were subjected to analysis of variance using the general linear model, univariate test procedure of SPSS ver. 21.0 (IBM Corp, Armonk, NY). Where analysis of variance indicated a significant study effect or interaction data were presented separately by study. Mean separation procedures were then performed using Tukey's HSD at the $P \leq 0.05$ level.

Results

Environmental Conditions During the Study

Annual precipitation at the site was close to normal for both years 1 and 2, however rainfall was higher in year 1 during late spring and unusually high amounts were observed during August of year 2. The month of July saw the least amount of rain for both years totaling just 16 mm. Reference evapotranspiration was also the highest during the month of July for both years averaging 6.8 mm per day (Table 2.1).

Table 2.1. Weather data for the 2014/2015 establishment period as well as years 1 and 2 of the study. Data are presented for September 2014 through October 2016. Data were obtained through an on-site weather station, which is part of the Texas ET Network.

	Month	ET_0	Precipitation	Average Temperature			Avg. Relative Humidity	Avg. Solar Radiation	Avg. Wind speed
				Mean	Low	High			
		------mm------		----------------^{0}C----------------			--%--	--MJm2--	--m/s--
2014	Sept.	148	152	25.6	21.7	31.0	68.6	17.3	2.1
	Oct.	126	59	21.5	16.4	27.4	64.7	15.5	2.2
	Nov.	85	139	12.2	7.5	18.0	62.8	10.7	2.8
	Dec.	57	67	12.7	8.6	17.4	73.8	7.5	2.6
2015	Jan.	58	81	9.2	4.1	15.4	59.0	11.3	2.4
	Feb.	63	19	10.9	5.7	16.7	66.4	11.8	2.9
	Mar.	87	84	15.7	10.0	21.6	70.1	14.3	2.3
	Apr.	122	125	20.5	16.5	25.5	72.5	15.2	2.7
	May	131	128	23.2	19.6	27.5	75.7	15.1	3.0
	Jun.	161	117	26.6	22.8	31.1	69.7	20.4	2.1
	Jul.	204	12	28.3	24.0	33.7	65.6	22.5	2.6
	Aug.	201	30	28.6	23.6	34.5	58.9	21.3	2.1
	Sept.	156	26	26.1	21.5	32.0	62.1	17.8	1.9
	Oct.	136	219	22.2	16.9	28.3	57.5	14.3	2.5
	Nov.	75	120	15.7	11.6	20.4	71.2	8.8	2.5
	Dec.	70	208	13.5	8.6	19.3	71.0	9.2	2.5
2016	Jan.	73	32	9.3	4.9	15.6	61.8	11.1	2.2
	Feb.	106	30	13.4	8.2	20.0	54.2	15.1	2.6
	Mar.	130	101	17.4	13.0	23.2	63.2	16.3	3.0
	Apr.	131	125	19.6	15.2	25.1	66.1	17.3	2.5
	May	134	305	22.1	18.6	27.0	71.1	16.5	2.4
	Jun.	168	56	26.7	23.1	31.9	67.1	20.7	1.9
	Jul.	211	4	28.7	24.8	34.3	63.3	22.1	2.6
	Aug.	161	175	27.2	23.8	32.4	69.7	18.2	1.9
	Sept.	136	51	26.1	22.3	31.3	67.1	17.4	1.6
	Oct.	122	60	22.3	17.5	28.8	63.8	15.1	1.7

Table 2.2. Analysis of variance for measured parameters for the fine sandy loam subsoil study.

	P-values										
	Establishment		Green Cover	Turf Quality	VWC			Root Length		Root Mass	
	Green Cover	VWC			0-5	0-10	0-20	Sand-cap	Subsoil	Sand-cap	Subsoil
					----------cm----------						
Cap Depth (CD)	***	***	***	***	***			***	***	***	***
Irrigation (I)			*	NS	**	**	NS	NS	NS	NS	NS
Date (D)			***	***	***	***	***	**	***	*	NS
CD x I			NS	NS	NS			NS	NS	NS	NS
CD x D			***	***	***			**	NS	*	NS
I x D			*	NS	*	NS	NS	NS	NS	NS	NS
CD x I x D			NS	NS	NS			NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001

Table 2.2. Continued.

P-values					
	SAR	EC	Organic Matter	Shear Strength	Water Penetration
Cap Depth (CD)	*	***	**	NS	***
Irrigation (I)		NS	NS	NS	NS
Date (D)	***	***	***		
CD x I		NS	NS	NS	NS
CD x D	NS	***	NS		
I x D		NS	NS		
CD x I x D		NS	NS		

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001

Table 2.3. Analysis of variance for measured parameters for the clay loam subsoil study.

	P-values													
	Establishment		Green Cover	Turf Quality	VWC			Root Length		Root Mass		SAR	EC	Shear Strength
	Green Cover	VWC			0-5	0-10	0-20	Sand-cap	Subsoil	Sand-cap	Subsoil			
					--------------cm--------------									
Cap Depth (CD)	***	***	***	***	***			***	***	***	***	***	***	NS
Irrigation (I)			NS	NS	NS	***	NS	NS	NS	NS	NS		NS	NS
Date (D)			***	***	***	***	***	NS	***	*	*	***	NS	
CD x I			NS	NS	NS			NS	NS	NS	NS		NS	NS
CD x D			***	***	***			NS	NS	NS	NS	***	***	
I x D			NS	NS	NS	*	NS	NS	NS	NS	*		NS	
CD x I x D			NS	NS	NS			NS	NS	NS	NS		NS	

NS, *, **, *** Nonsignificant or significant at *P* = 0.05, 0.01, or 0.001

Percent Green Cover during Establishment

There was a significant capping depth main effect on percent green cover for the sandy loam subsoil (Table 2.2; Figure 2.1). Percent green cover ranged from 40 to 85 percent, eight weeks after sprigging. The highest coverage was observed on the 0 cm capping depth plots, followed by the 5 cm capping depth. The deepest capping depth of 20 cm led to significantly delayed establishment compared to the other shallower capping depths. This was likely due in part to lower soil moisture content at the surface of the 20 cm san-capped root zone compared to the other treatments.

The capping depth main effect on percent green cover was also significant for the clay loam subsoil (Table 2.3; Figure 2.2) Percent green coverage ranged from 45 to 65% eight weeks after sprigging. As was found with the fine sandy loam subsoil, the highest coverage was observed on the 0 cm capping depth. However, the 5, 10, and 20 cm capping depth treatments did not significantly differ from one another.

Volumetric Water Content during Establishment

Capping depth had a significant main effect on volumetric water content within the surface (0 to 5 cm) of the fine sandy loam sand-cap (Table 2.2; Figure 2.3). Volumetric water content at the 0 to 5 cm depth ranged from 15 to 35%. Volumetric water content was highest on the 0 cm (topdressed only) plots and lowest on the 20 cm capping depth treatments.

Capping depth also had a significant main effect on volumetric water content within the surface (0 to 5 cm) of the clay loam subsoil (Table 2.3; Figure 2.4). Volumetric water content at the 0 to 5 cm depth fluctuated from 12 to 40% during the study period for the clay loam plots. Volumetric water content was highest for the 0 cm capping depth and decreased with increasing capping depth. There was also a significant difference between each of the capping depths when grown atop the clay loam subsoil.

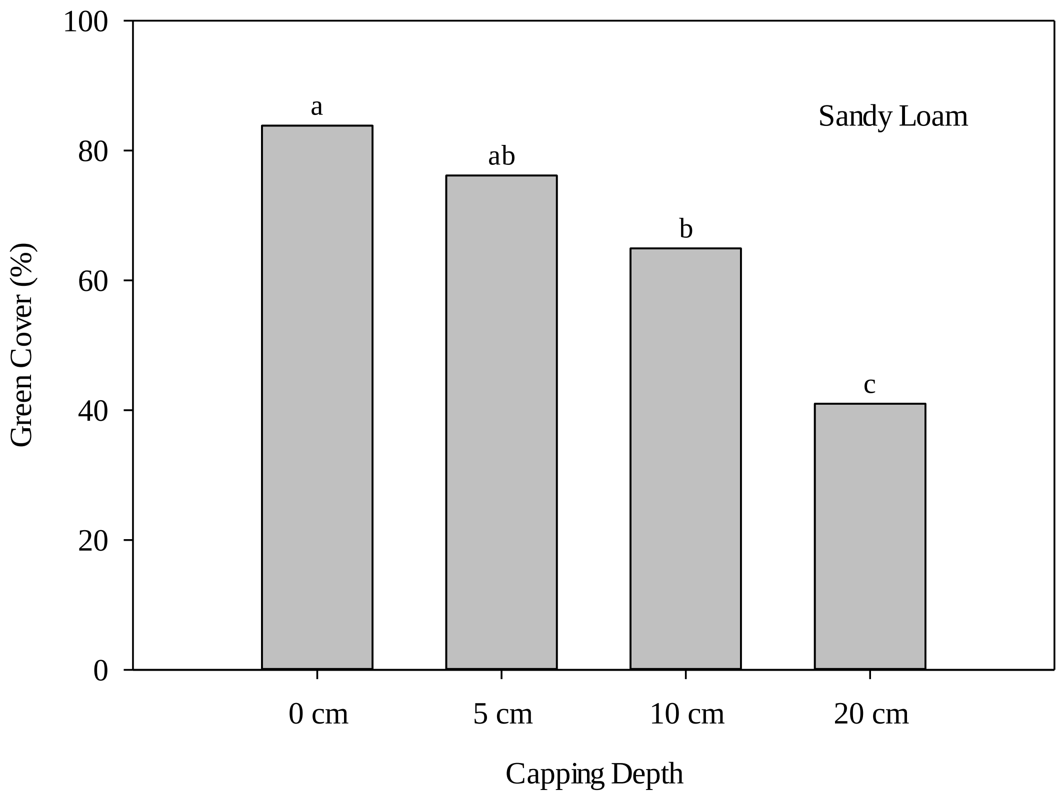

Figure 2.1. Percent green cover during establishment as affected by capping depth on the sandy loam subsoil. Percent green cover was evaluated through digital image analysis eight weeks after sprigging. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

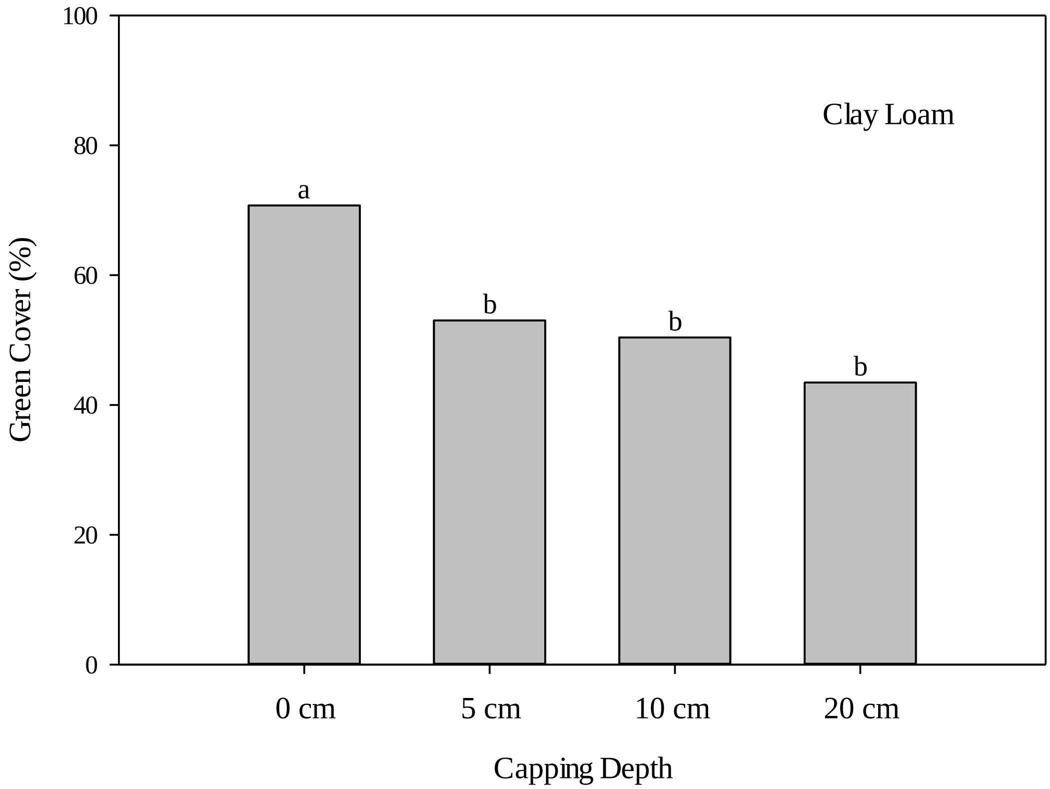

Figure 2.2. Percent green cover during establishment as affected by capping depth on the clay loam subsoil. Percent green cover was evaluated through digital image analysis eight weeks after sprigging. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

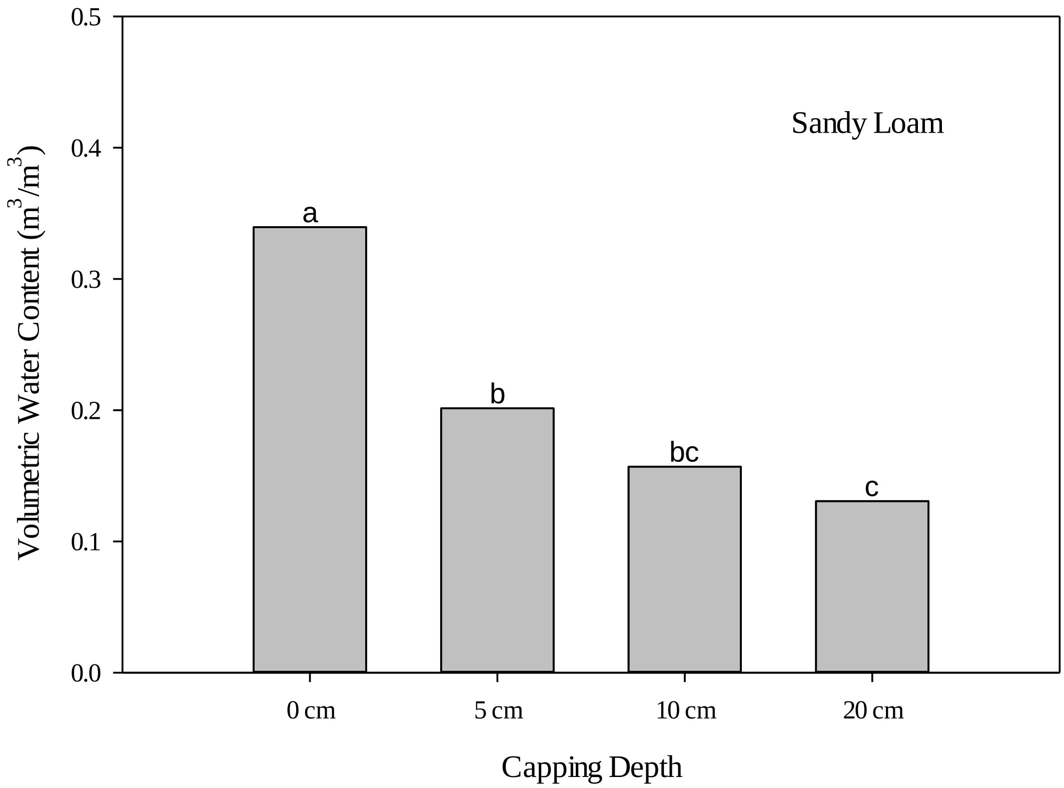

Figure 2.3. Volumetric water content 0 to 5 cm during establishment as affected by capping depth on the sandy loam subsoil. Volumetric water content was measured prior to irrigating eight weeks after sprigging. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$

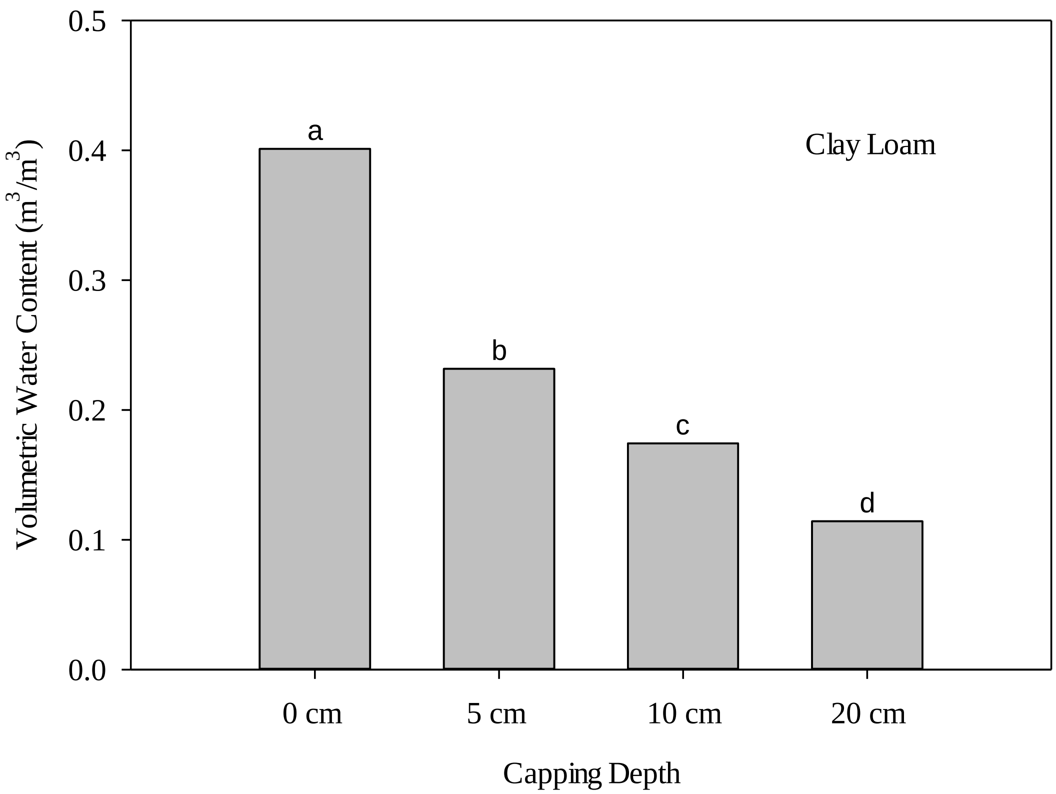

Figure 2.4. Volumetric water content 0 to 5 cm during establishment as affected by capping depth on the clay loam subsoil. Volumetric water content was measured prior to irrigating eight weeks after sprigging. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$

Percent Green Cover

There was an irrigation by date interaction for percent green cover for the fine sandy loam subsoil (Table 2.2; Figure 2.5). August 2015 was the only period during year 1 where a significant difference was detected between the 1x and 2x wk^{-1} irrigation frequencies. This difference may have been partially a result of vertical mowing during mid-summer, which, although performed across all plots, may have produced a greater degree of stress on the 1x wk^{-1} irrigation frequency treatment. During year 2, no detectable differences were observed at any time between the 1x and 2x wk^{-1} irrigation frequencies.

In addition on the fine sandy loam subsoil, the 0 cm (topdressed only) plots consistently maintained the highest levels of percent green cover relative to other treatments throughout both years of the study (Figure 2.6). The 5 and 10 cm capping depth treatments performed similarly in terms of percent green cover, and were never significantly different from each other. The 20 cm sand-cap dropped to below 60% cover during the first half of August in both years. Again, this may have been primarily due to the vertical mowing even, which took place in July, but was also likely affected by the limited rainfall and high ET_o rates occurring at this time. Regardless, following late summer rainfall events, percent green cover noticeably increased within all treatments from August to September during both years.

Throughout both years, topdressed plots maintained greater percent green cover than all other treatments on the clay loam subsoil, and never fell below 85% green cover (Figure 2.7). Additionally, the 5 and 10 cm capping depth treatments never significantly differed throughout both years. The 20 cm capping depth treatment never fell below 60 percent green cover, and statically differed on only 3 of 14 rating dates form the 5 and 10 cm capping depth treatments.

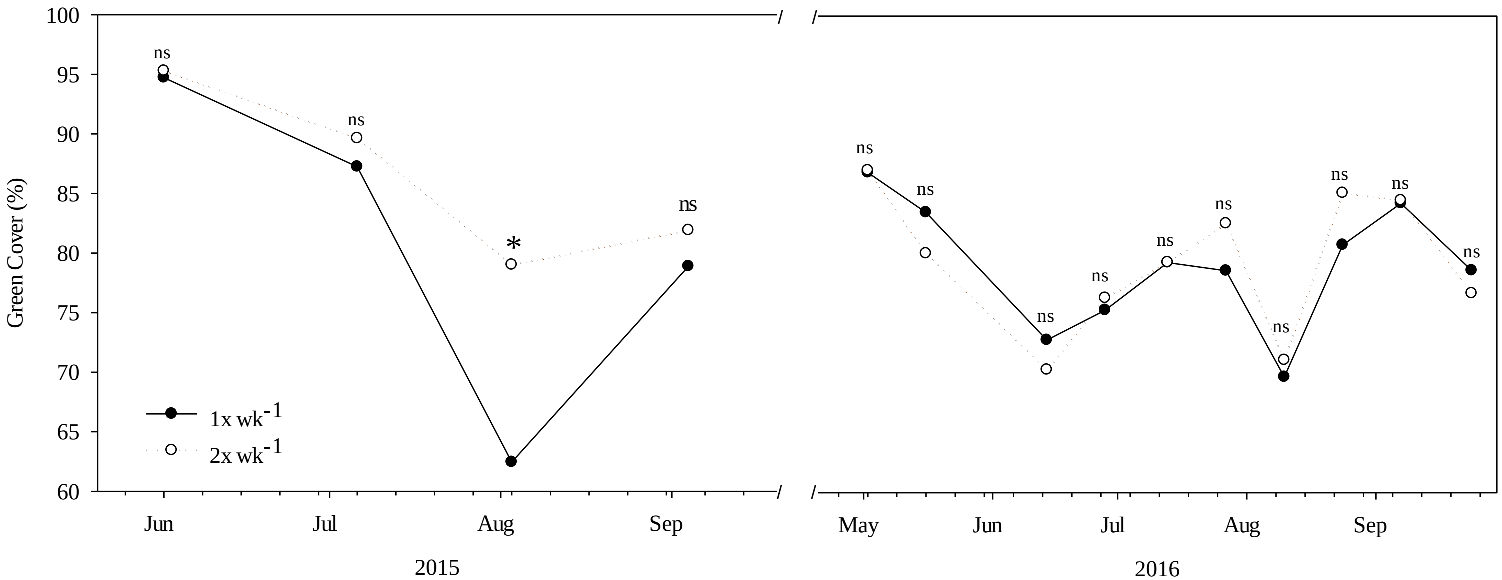

Figure 2.5. Percent green cover affected by irrigation frequencies on the sandy loam subsoil for the 2015 and 2016 seasons. Data are pooled across sand-capping treatments. Means with asterisks are significantly different based on Tukey's HSD at P≤ 0.05.

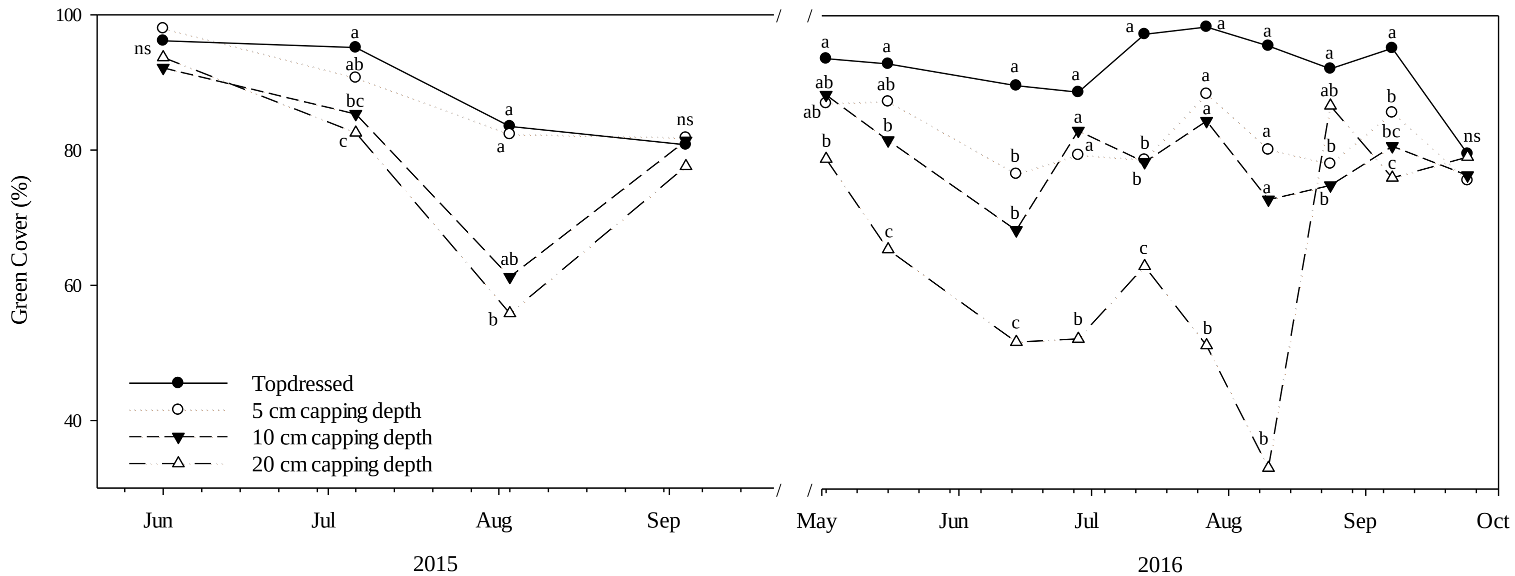

Figure 2.6. Percent green cover as affected by capping depth on the sandy loam subsoil for the 2015 and 2016 seasons. Data are pooled across irrigation treatments. Means with the same letter on the same date are not significantly different based on Tukey's HSD at p≤ 0.05.

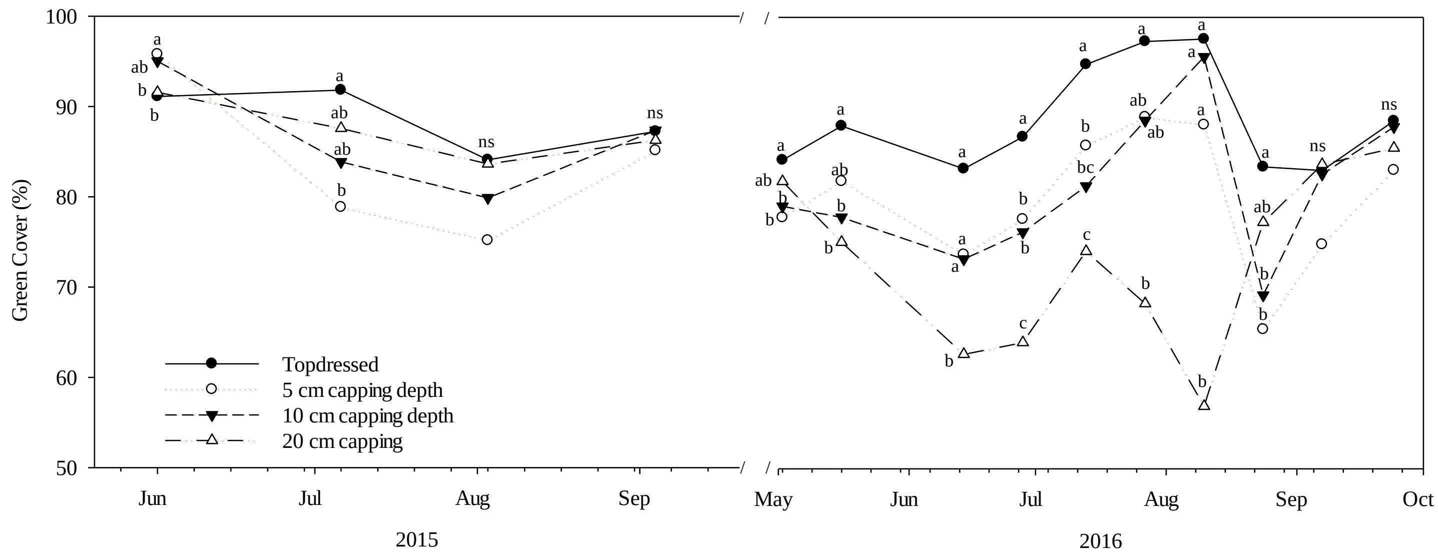

Figure 2.7. Percent green cover as affected by capping depth on the clay loam subsoil for the 2015 and 2016 seasons. Data are pooled across irrigation treatments. Means with the same letter at the same date are not significantly different based on Tukey's HSD at p≤ 0.05.

Visual Turf Quality

There was a significant capping depth by date interaction on visual turf quality on the fine sandy loam subsoil (Table 2.2; Figure 2.8). As such, the topdressed treatments maintained the highest turf quality on the majority of dates, and never dropped below a rating of 7.5 during 2016. Also on the fine sandy loam subsoil, the 5 and 10 cm capping depths never significantly differed from one another. The 20 cm capping depth plots were the only treatments to fall below acceptable visual quality (< 5), and during the 2016 season, dropped below the acceptable threshold on four out of 10 dates.

Finally, there was also a significant capping depth by date interaction on visual turf quality detected for the clay loam subsoil (Table 2.3; Figure 2.9). As such, all treatments sustained acceptable visual quality (≥ 5) throughout both seasons, and there were no differences between treatments for 7 of the 8 rating dates in year 1. However, during year 2, treatment differences were detected for all rating dates. Interestingly, the two deepest capping depths (10 and 20 cm), differed on only two of the 10 rating dates during the entire 2016 season.

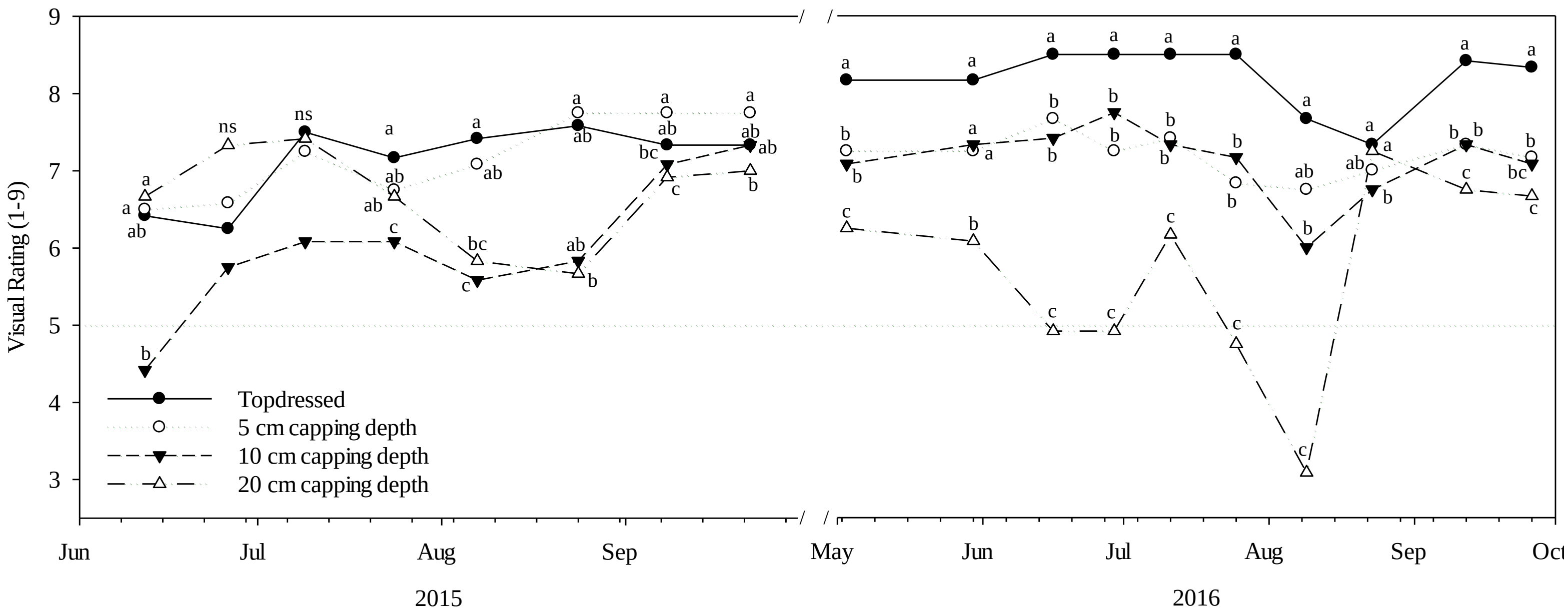

Figure 2.8. Turf quality as affected by capping depth on the sandy loam subsoil for the 2015 and 2016 seasons. Data were pooled across irrigation treatments. Means with the same letter at the same date are not significantly different based on Tukey's HSD at p≤ 0.05.

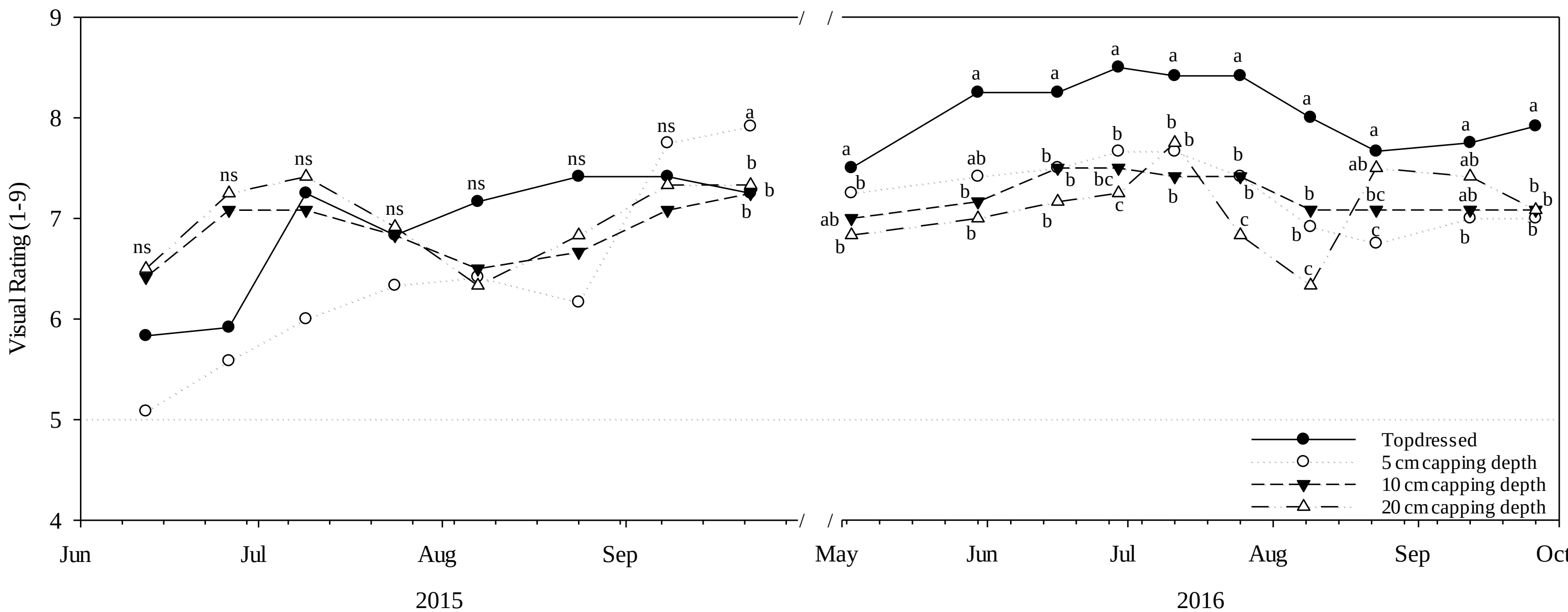

Figure 2.9. Turf quality as affected by capping depth on the clay loam subsoil for the 2015 and 2016 seasons. Data were pooled across irrigation treatments. Means with the same letter at the same date are not significantly different based on Tukey's HSD at p≤ 0.05.

Sand-Cap Volumetric Water Content

Once complete establishment was achieved, irrigation was supplied at amounts corresponding to 0.6 x ET_o, based on 40-year historical weather data, at frequencies of either 1x or 2x wk^{-1}. Volumetric water content measurements were taken for the 0 to 5 cm depth across all treatments, for the 0 to 10 cm depth in the 10 cm capping depth treatments, and for the 0 to 20 cm depth in the 20 cm capping depth treatments.

ANOVA detected a significant irrigation (frequency) by date interaction for the 0 to 5 cm volumetric water content on the fine sandy loam subsoils (Table 2.2 and 2.4). The month of July and rating date of 18 September were the only dates where significant 0 to 5 cm soil moisture differences occurred due to irrigation frequency. ANOVA also revealed a significant capping depth by date interaction for the 0 to 5 cm volumetric water content (Table 2.2; Figure 2.10). The topdressed plots maintained the highest 0 to 5 cm volumetric water content of all treatments across all dates, however, soil volumetric water content did decrease from October 2015 to October 2016, as topdressing of those treatments led to an increasing sand-cap layer depth. Volumetric water content within the 0 to 5 cm depth remained consistently lower on the 20 cm capping depth compared to the other treatments. Also, 5 and 10 cm capping depth treatments did not differ on 11 of the 13 rating dates atop the fine sandy loam subsoils.

ANOVA also detected significant main effect of irrigation and date for 0 to 10 cm volumetric water content (Table 2.2 and 2.5). Slightly elevated volumetric water content was periodically observed in the 2x wk^{-1} irrigation treatments, however, 0 to 10 cm volumetric water content of all treatments declined during the summer months in both years, likely due to higher ET demand and decreased rainfall.

ANOVA also detected a main effect of date on the 0 to 20 cm volumetric water content (Table 2.2). Similar to the 0 to 5 cm measurements, there was a trend toward lower volumetric water content during the dry summer months.

Table 2.4. Volumetric water content as affected by irrigation frequency for the 0 to 5 cm sand-cap depth on the sandy loam subsoil for the 2015 and 2016 seasons. Data are pooled across capping depth treatments. Means with the same letter at the same date are not significantly different based on Tukey's HSD at p≤ 0.05.

	2015		2016										
Irrigation Frequency	14-Sept	19-Oct	25-April	2-May	30-May	13-Jun	27-Jun	11-July	25-July	9-Aug	29-Aug	12-Sept	28-Sept
1x wk^{-1}	16.8 a	11.7 a	11.8 a	13.0 a	12.0 a	4.9 a	5.9 a	4.1 a	4.5 a	5.9 a	8.4 a	6.0 a	4.8 a
2x wk^{-1}	17.8 a	12.0 a	11.6 a	12.4 a	11.5 a	4.7 a	7.4 b	4.7 b	59 b	7.1 a	9.1 a	7.5 b	5.0 b

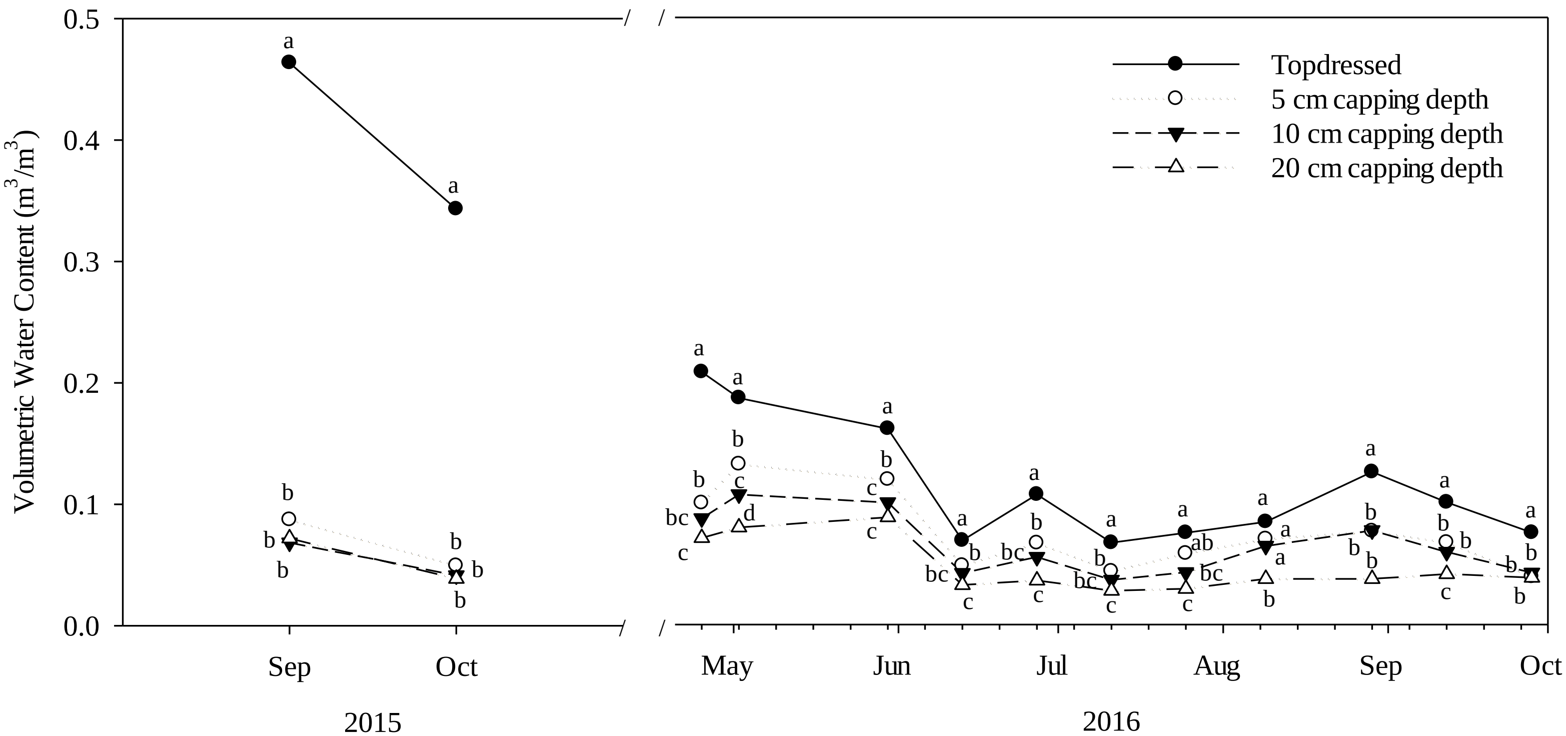

Figure 2.10. Volumetric water content within the 0 to 5 cm sand-cap depth as affected by capping depth on the sandy loam subsoil during 2015 and 2016 seasons. Data are pooled across irrigation treatments. Means with the same letter on a given date are not significantly different based on Tukey's HSD at p≤ 0.0

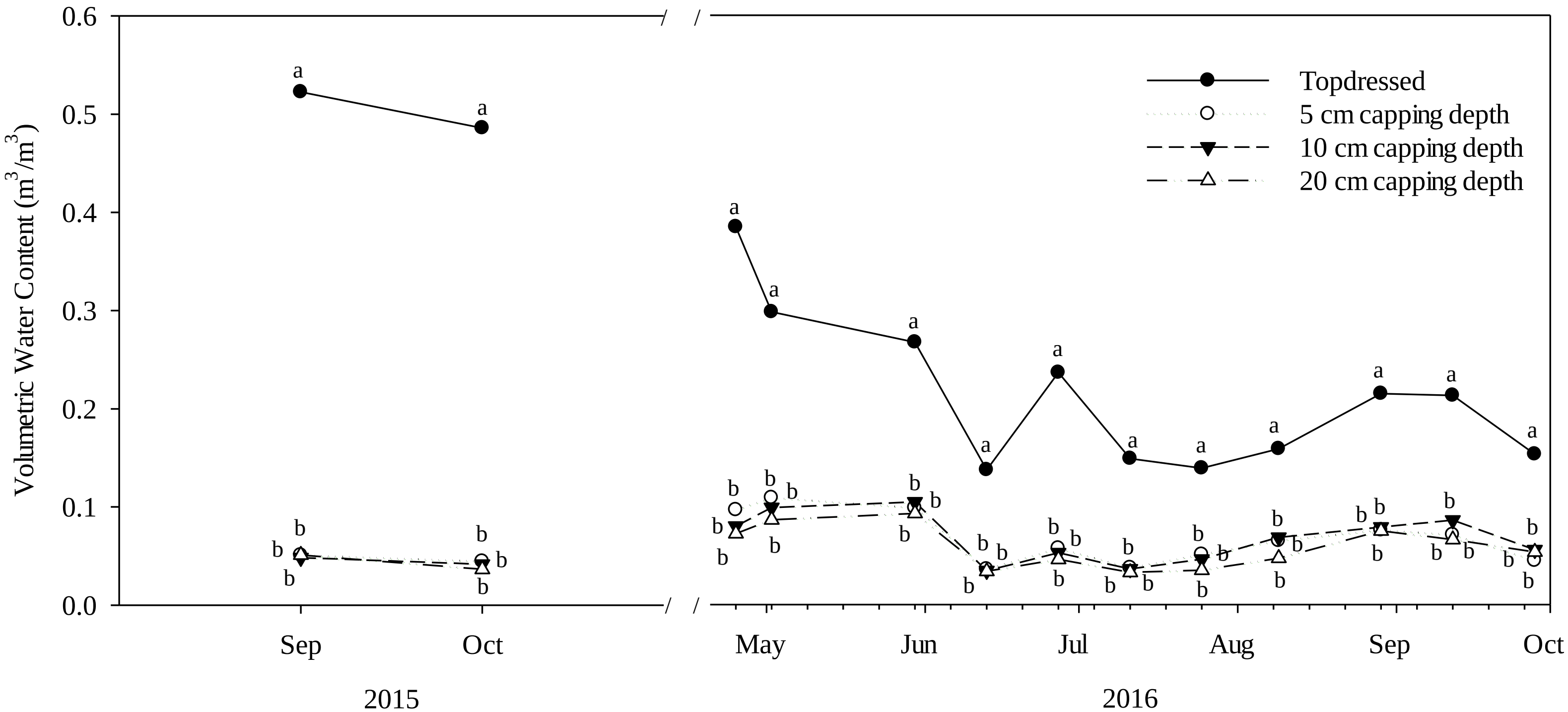

Figure 2.11. Volumetric water content within the 0 to 5 cm sand-cap depth as affected by capping depth on the clay loam subsoil during 2015 and 2016 seasons. Data are pooled across irrigation treatments. Means with the same letter on a given date are not significantly different based on Tukey's HSD at p≤ 0.05

Table 2.5. Volumetric water content for the 0 to 10 cm sand-cap depth on the fine sandy loam as affected by irrigation frequencies for the 2015 and 2016 seasons. Means with the same letter at the same date are not significantly different based on Tukey's HSD at p≤ 0.05

	2015		2016										
Irrigation Frequency	14-Sept	19-Oct	25-April	2-May	30-May	13-Jun	27-Jun	11-July	25-July	9-Aug	29-Aug	12-Sept	28-Sept
1x wk^{-1}	11.4 a	9.7 a	11.4 a	14.3 a	14.0 a	4.9 a	7.3 a	5.3 a	5.6 a	7.6 a	11.1 a	9.1 a	8.1 a
2x wk^{-1}	12.1 a	11.7 b	10.7 a	14.3 a	14.7 a	5.2 a	9.3 a	5.2 a	7.2 a	10.7 a	11.6 a	15.8 b	8.1 a

Root Development Effects

ANOVA detected a significant capping depth by date interaction for total root length within the sand-cap for fine sandy loam soil (Table 2.2). Total root length within sand-cap increased in all capping depth treatments from year 1 to year 2 atop fine sandy loam subsoil (Figure 2.12). The greatest increase was observed within the 20 cm capping depth, increasing from 450 cm to 975 cm in total root length. After year 1, the 10 cm and 20 cm capping depth treatments did not significantly differ with regard to total root length, however, in year 2 all capping depth treatments significantly differed from one another. After year 2, the 20 cm capping depth had the highest total root length followed by the 10 cm capping depth and 5 cm capping depth, respectively.

ANOVA detected main effects of both capping depth and date for total root length within fine sandy loam subsoil (Table 2.2). The data showed that total root length increased from year 1 to year 2 in this subsoil for all sand-cap and irrigation treatments. When pooled across years, total root length within the fine sandy loam subsoil averaged between 225 and 750 cm (Figure 2.13). The deepest capping depth of 20 cm led to significantly fewer subsoil roots compared to all other sand-cap treatments. This suggests that fewer roots develop into the subsoil as sand-cap depth increases.

ANOVA also revealed a significant main effect of capping depth on total root length within the sand-cap for clay loam subsoil (Table 2.3). Total root length within the sand-cap ranged from 600 cm on the 5 cm cap to 1400 cm on the 20 cm cap (Figure 2.14). Again, an overall trend of increasing total sand-cap root length with deeper capping depth was observed.

There were also significant capping depth and date main effects on total root length within the clay loam subsoil (Table 2.3; Figure 2.15). A similar trend in higher total root length within the clay loam subsoil on shallower capping depth treatments was also observed. The 20 cm capping depth atop clay loam subsoil resulted in significantly less total root length than all other treatments, with only ~380 cm of total root length.

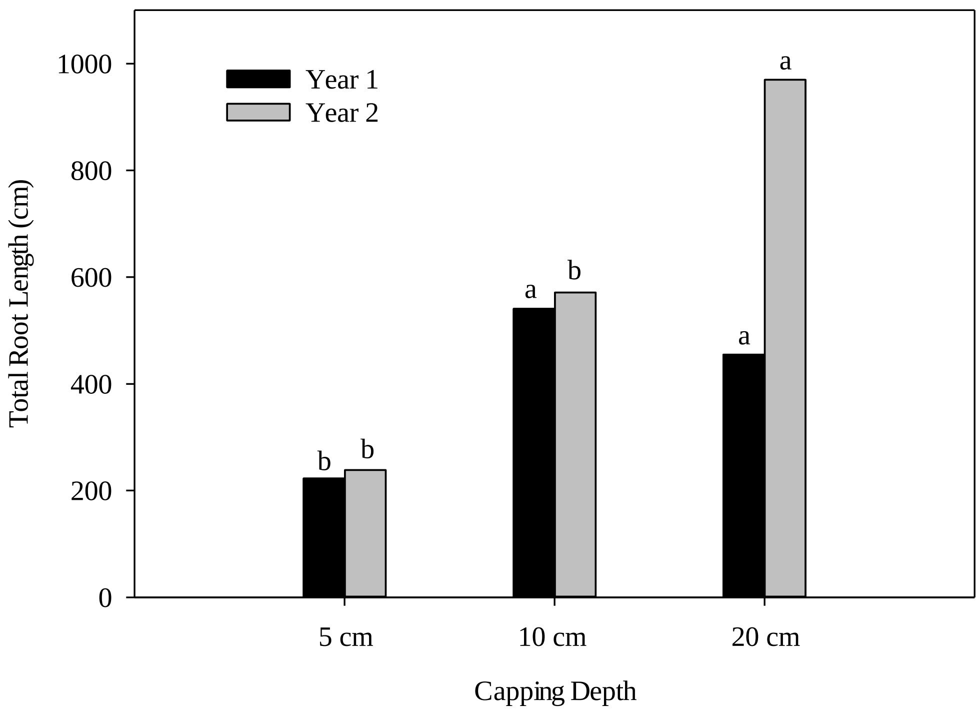

Figure 2.12. Total root length within the sand-cap as affected by capping depth on the sandy loam subsoil for years 1 and 2. Core samples were 5 cm diameter by the corresponding capping depth. Data are pooled across irrigation treatments. Means with the same letter within the same year are not significantly different based on Tukey's HSD at $p \leq 0.05$.

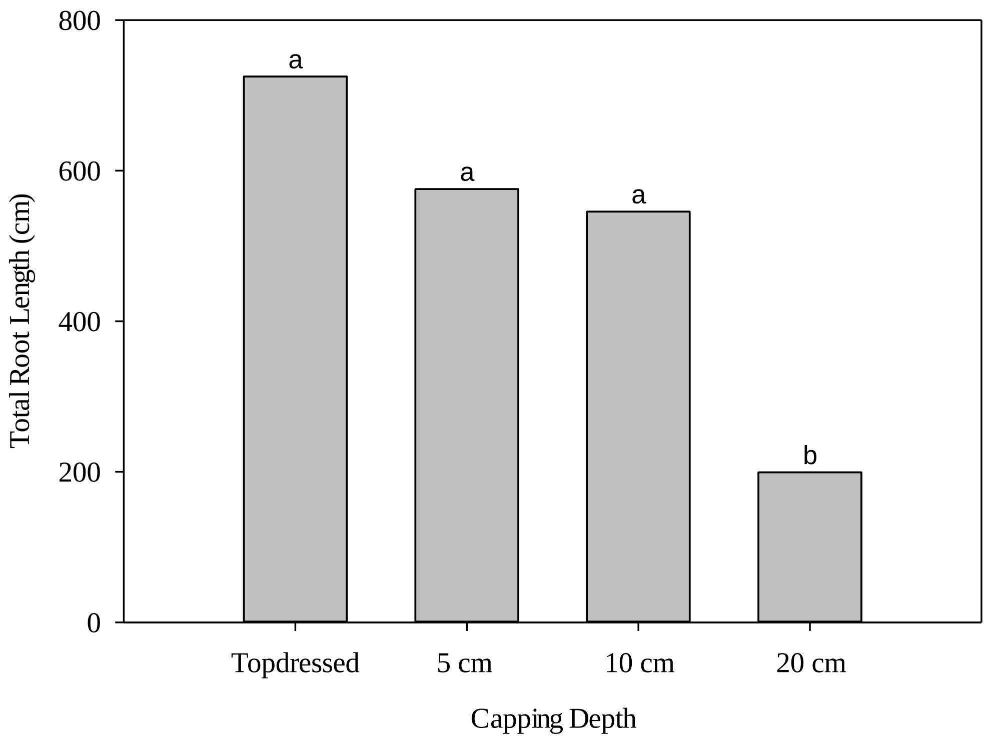

Figure 2.13. Total root length within the sandy loam subsoil as affected by capping depth. Core samples were 5 cm diameter by 30 cm deep. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

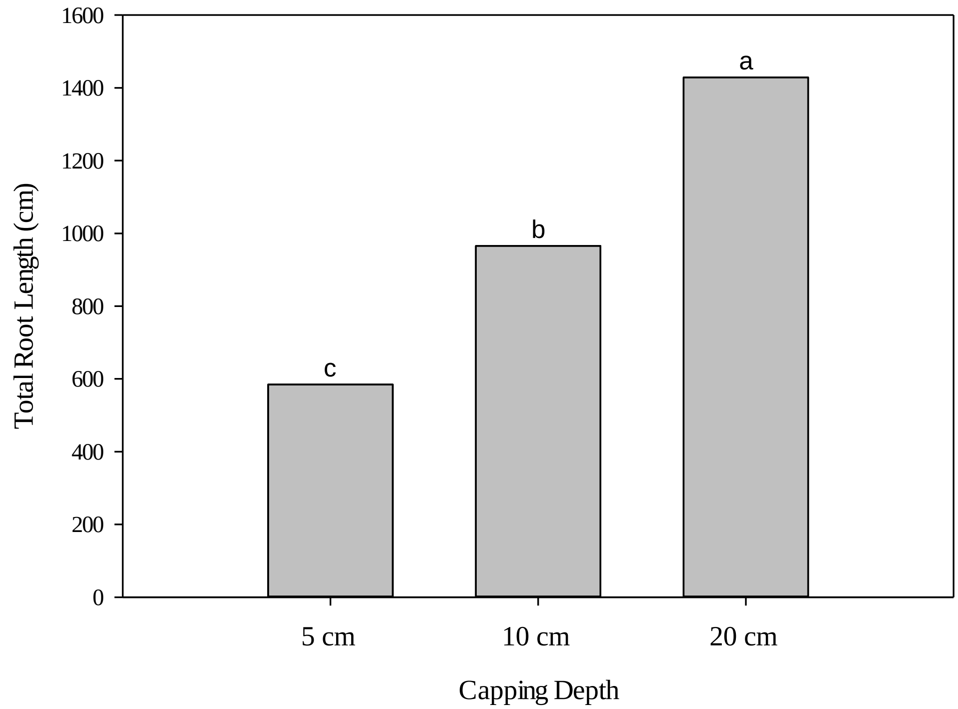

Figure 2.14. Total root length within the sand-cap on the clay loam subsoil as affected by capping depth. Core samples were 5 cm diameter by the corresponding capping depth. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Turkey's HSD at $p \leq 0.05$.

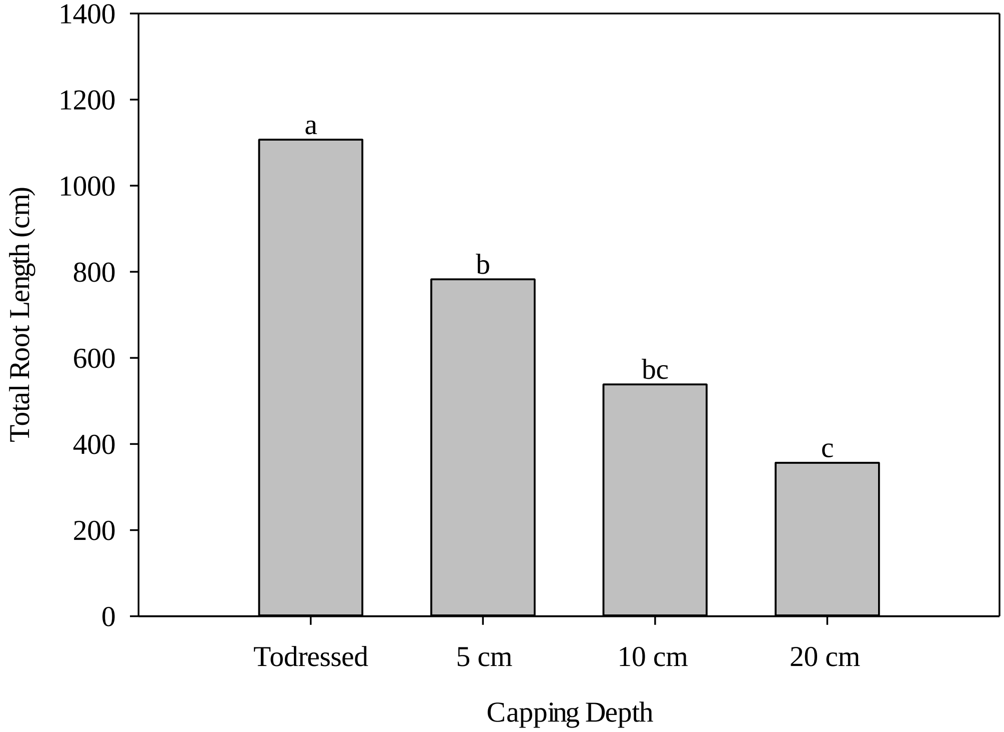

Figure 2.15. Total root length within in the clay loam subsoil as affected by capping depth. Core samples were 5 cm diameter by 30 cm deep. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

Root Mass Effects

ANOVA detected a significant capping depth by date interaction for root mass within the sand-cap of fine sandy loam subsoils (Table 2.2). Root mass within the sand-capwas affected by sand-capping depth both years for the fine sandy loam subsoil, ranging from 40.5 to 89 mg in year 1, and from 33.5 to 187 mg in year 2 (Table 2.6). The greatest root mass was observed within the 20 cm capping depth.

There was also a capping depth main effect on root mass within the fine sandy loam subsoil (Table 2.2). The greatest subsoil root mass (90 mg) was associated with the 0 cm topdressed treatments (Figure 2.16). Similar to total root length, as capping depth increased, root mass also decreased within the underlying fine sandy loam subsoil. As such, the 20 cm capping depth possessed significantly fewer roots (30 mg) than all other treatments (60, 70, and 90 mg for 10, 5, and 0 cm sand-caps, respectively).

There were also significant effects of both capping depth and date on sand-cap root mass atop clay loam subsoils (Table 2.3). When pooled across sand-capping and irrigation treatments, sand-cap root mass increased from 120 mg in year 1 to 160 mg in year 2 atop clay loam subsoils. Sand-cap root mass was almost 3 times higher in the 20 cm sand-cap treatment than in the5 cm treatment (Figure 2.17).

ANOVA detected an irrigation by date interaction as well as capping depth main effect on root mass within clay loam subsoils (Table 2.3). Irrigation frequency did not significantly affect root mass in the clay loam subsoil in year 1, however, in year 2, the 2x w^{-1} irrigation led to increased root mass (Table 2.7). Greater root mass development also occurred in the clay loam subsoil in the topdressed treatment, and decreased as the capping depth layer increased (Figure 2.18). The 5 cm and 10 cm capping depth treatments were not significantly different from each other, but had over 2 times the subsoil root mass as compared to the deeper 20 cm capping depth (Figure 2.18)

Table 2.6. Root mass within the sand-cap atop the sandy loam subsoil as affected by capping depth for years 1 and 2. Core samples were 5 cm diameter by the corresponding capping depth. Data are pooled across irrigation treatments. Means with the same letter within a given year are not significantly different based on Tukey's HSD at $p \leq 0.05$.

Capping Depth	Year 1	Year 2
	---------mg----------	
5 cm	40.5b	33.5 a
10 cm	82.0 b	105.0 a
20 cm	89.0 a	187.0 a

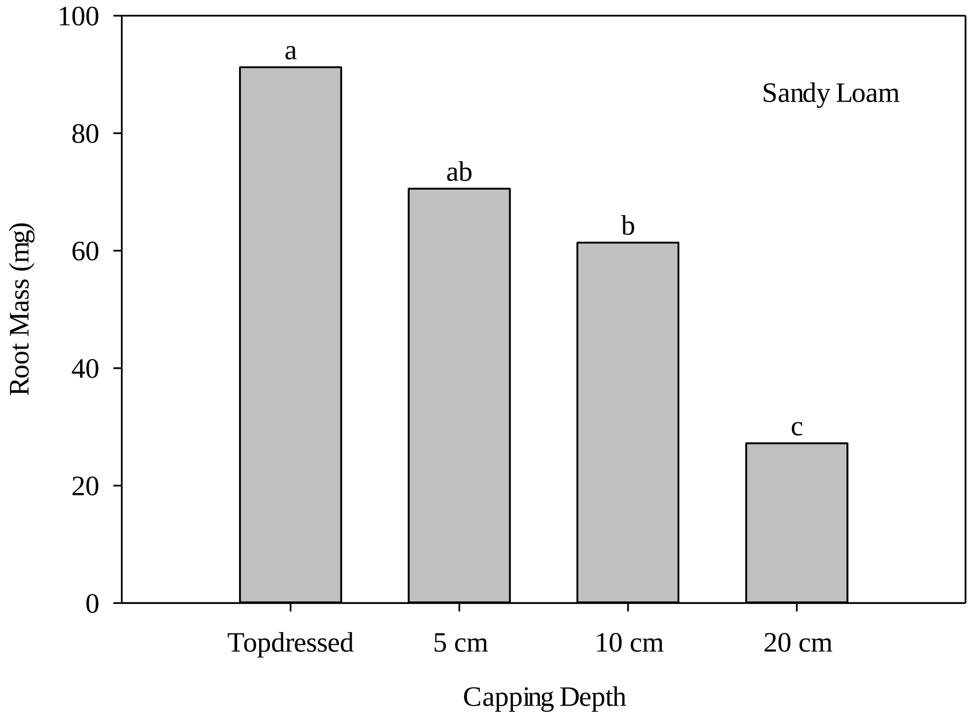

Figure 2.16. Root mass within the sandy loam subsoil as affected by capping depth. Core samples were a 5 cm diameter by 30 cm deep. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$

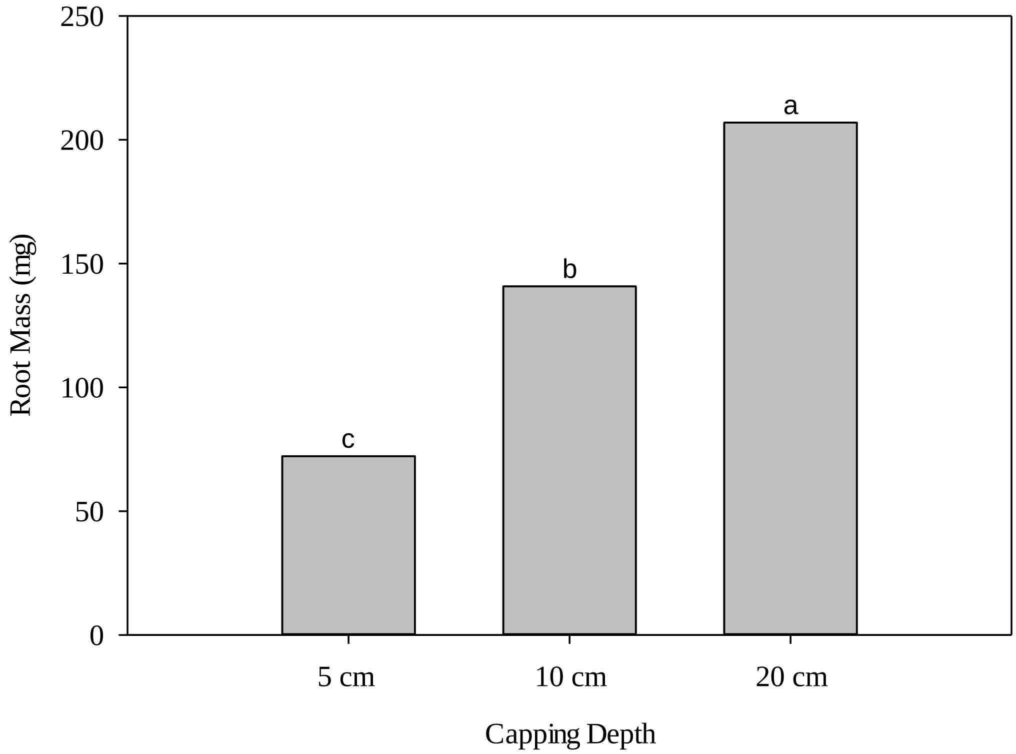

Figure 2.17. Root mass within the sand-cap atop the clay loam subsoil as affected by capping depth. Core samples were a 5 cm diameter by the corresponding capping depth. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

Table 2.7. Root mass within the clay loam subsoil as affected by irrigation frequency for years 1 and 2. Core samples were 5 cm diameter by 30 cm deep. Data are pooled across capping depth treatments. Means with the same letter for a given year are not significantly different based on Tukey's HSD at p≤ 0.05

Irrigation Frequency	Year 1	Year 2
	---------mg----------	
$1x/w^{-1}$	76.5 a	78.5 b
$2x/w^{-1}$	71.5 a	104.0 a

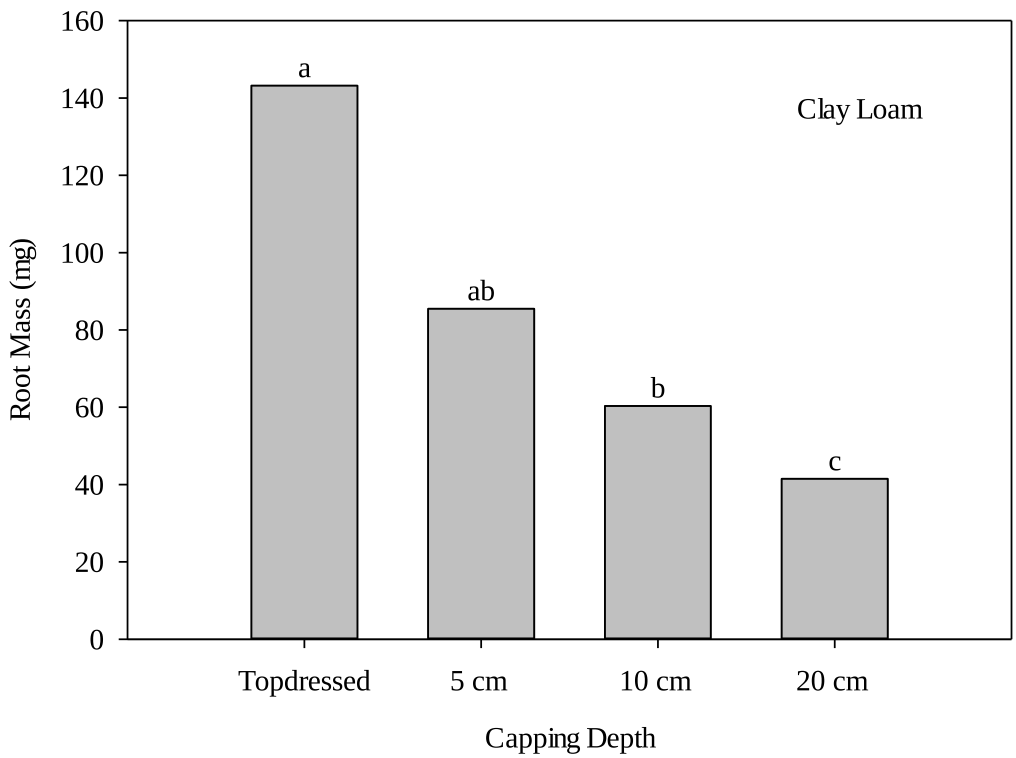

Figure 2.18. Root mass within the clay loam subsoil as affected by capping depth. Core samples were 5 cm diameter by 30 cm deep. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at p≤ 0.05

Sodium Adsorption Ratio (SAR)

ANOVA detected both significant date and capping depth main effects on SAR for fine sandy loam subsoils. SAR quickly increased in the fine sandy loam throughout the seasons due to the high amounts of sodium in the irrigation water. The mean SAR value was highest for the topdressed treatments and the rate of increase was slightly delayed by sand-capping (Figure 2.19). The SAR of the 10 cm and 20 cm capping depth treatments were not significantly different from each other.

A capping depth by date interaction was detected for SAR within clay loam subsoils. Sodium adsorption ratio within the clay loam subsoil also increased over the two-year period. SAR of the 10 and 20 cm capping depth treatments increased at every sampling date, while the topdressed treatments fluctuated more throughout the two years. This may be due to the natural precipitation events that occurred throughout each season that helped flush the sodium downward out of the subsoil surface.

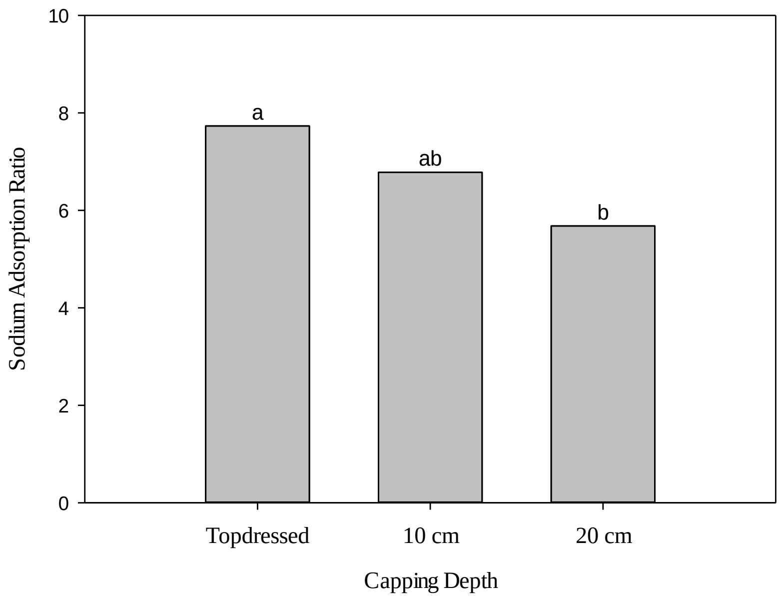

Figure 2.19. Sodium adsorption ratio within the 0 to 2.5 cm depth of the sandy loam subsoil as affected by capping depth. Data are pooled across sampling dates. Means with the same letter are not significantly different based on Tukey's HSD at p≤ 0.05.

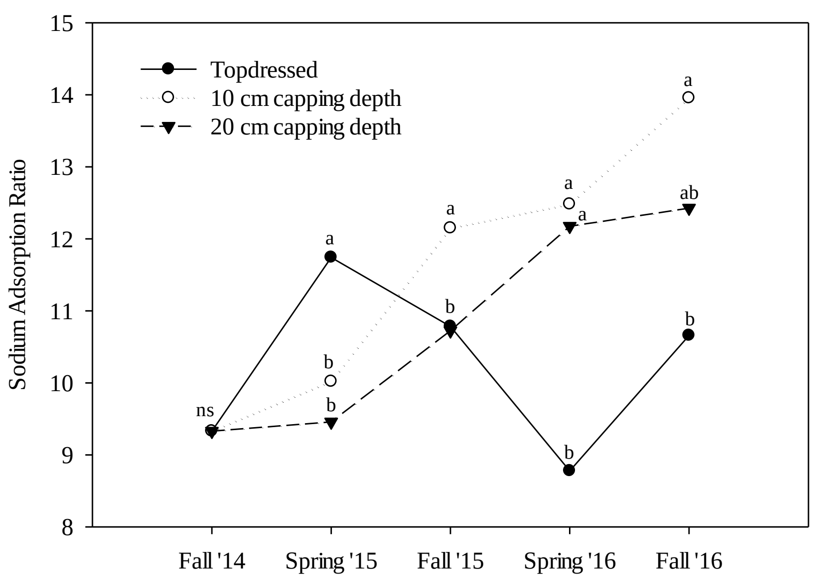

Figure 2.20. Effect of capping depth by date on sodium adsorption ratio within the 0 to 5 cm depth of clay loam subsoil. Means with the same letter are not significantly different based on Tukey's HSD at p≤ 0.05.

Electrical Conductivity (EC)

ANOVA revealed a capping depth by date interaction for sand-cap treatments atop fine sandy loam subsoils (Tables 2.2). Within these sand-caps, EC measurements on the topdressed treatments remained higher compared to all the other treatments throughout year 2, and were highest during the month of August (Table 2.8). However, EC values remained the lowest on the 20 cm capping depth treatments during the 2016 season. Due to the unusual amount of rainfall in late August of 2016 (Table 2.1), EC values decreased considerably within all treatments in September.

A significant capping depth by date interaction also occurred for the clay loam subsoil treatments (Tables 2.3 and 2.9). EC measurements generally decreased as the capping depth increased. Topdressed treatments also had significantly higher EC measurements on five of the six measurement dates, while the other three treatments were not significantly different from each other on five of the six dates, also.

Table 2.8. Year 2 electrical conductivity at the 2.5 cm depth of sand-cap as affected by capping depth on the sandy loam subsoil. Data are pooled across irrigation treatments. Means with the same letter on a given date are not significantly different based on Tukey's HSD at p≤ 0.05.

Sandy Loam Subsoil						
Capping Depth	26-Apr	3-May	10-June	10-July	9-Aug	13-Sept
			-------- dS m^{-1}--------			
Topdressed	0.09 a	0.23 a	0.47 a	0.44 a	0.44 a	0.26 a
5 cm	0.08 a	0.07 b	0.10 b	0.11 b	0.11 b	0.01 b
10 cm	0.08 a	0.08 b	0.08 bc	0.09 bc	0.08 bc	0.01 b
20 cm	0.06 b	0.05 b	0.05 c	0.06 c	0.05 c	0.01 b

Table 2.9. Year 2 electrical conductivity at the 2.5 cm depth of sand-cap as affected by capping depth on the clay loam subsoil. Data are pooled across irrigation treatments. Means with the same letter on a given date are not significantly different based on Tukey's HSD at p≤ 0.05.

Clay Loam Subsoil						
Capping Depth	26-Apr	3-May	10-June	19-July	9-Aug	13-Sept
			-------- dS m^{-1}-------			
Topdressed	0.10 a	0.15a	0.14 a	0.16 a	0.16 a	0.27 a
5 cm	0.09 b	0.08 b	0.06 b	0.08 b	0.07 ab	0.02 b
10 cm	0.07 b	0.07 b	0.06 b	0.08 b	0.07 b	0.02 b
20 cm	0.07 b	0.05 b	0.05 b	0.05 b	0.05 c	0.20 b

Organic Matter Accumulation

ANOVA showed both cap depth and date main effects on sand-cap organic matter atop fine sandy loam soils. When pooled across capping depth treatments, percent organic matter increased by 2% from fall of year 1 to fall of year 2 on the sandy loam subsoil. However, no significant differences were observed between the 5, 10, and 20 cm capping depth treatments. The topdressed plots retained 2-3% higher organic matter compared to the other treatments, likely due to the presence of native soil organic matter in these samples.

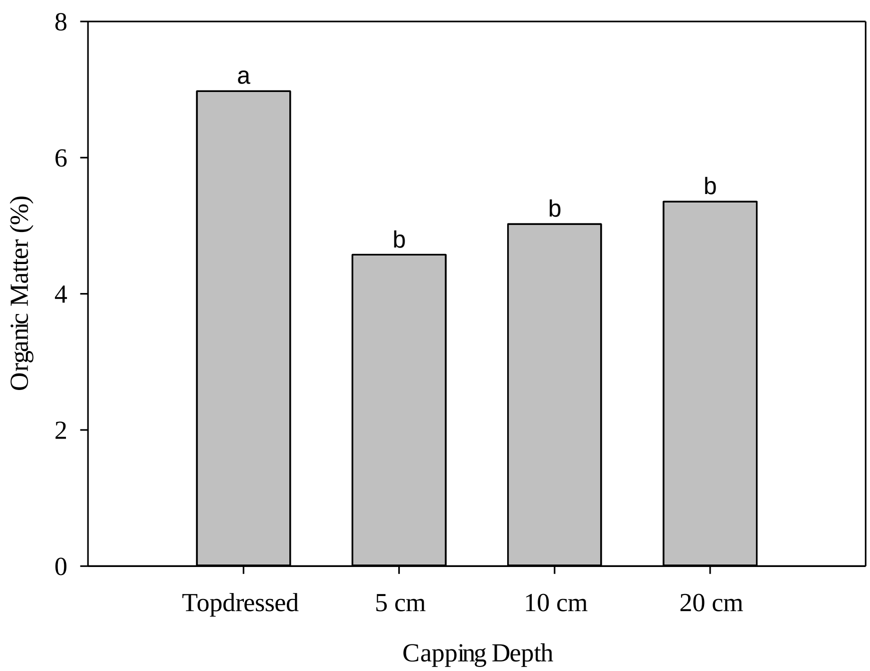

Figure 2.21. Organic matter accumulation within the upper 0 to 2.5 cm depth of sand-cap as affected by capping depth on the sandy loam subsoil. Data are pooled across irrigation treatments and years. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

Hydrophobicity

Hydrophobicity was only observed within the 0 to 1.3 cm depth on the deeper capping depths of 10 and 20 cm. The WDPT means for the 10 and 20 cm capping depths were 126 and 210 seconds and is classified at strongly water repellent. Topdressed plots and the 5 cm capping depth showed no sign of hydrophobicity and fell under the wettable classification.

Table 2.10. WDPT within the 1.3 cm depth on the sandy loam as affected by capping depth. Data are pooled across irrigation treatments. Means with the same letter are not significantly different based on Tukey's HSD at $p \leq 0.05$.

Capping Depth	WDPT	Classification
	-----s-----	
Topdressed	<5 b	wettable
5 cm	<5 b	wettable
10 cm	126 ab	strongly water repellent
20 cm	210 a	strongly water repellent

Discussion

Establishment of Sand-Capped Systems

Eight weeks after sprigging, one of the most important factors driving establishment of plots appeared to be soil moisture retention at or near the surface of the sand-caps. Significantly lower soil volumetric water content measurements were detected at the 0 to 5 cm depth for the deeper capping depths. Percent green cover exhibited a corresponding decrease as the capping depth increased on the sandy loam and clay loam subsoils.

Nutrient availability during establishment of turfgrasses is another import factor to consider, and could have influenced establishment in a similar manner to that of soil moisture. Rodrigez et al. (2001) reported that N:P:K ratios significantly affected establishment rates of various turfgrass species , including Tifway bermudagrass. It is possible that nutrient availability differences due to sand-cap depth treatments and proximity to subsoil could have also influenced establishment of Tifway bermudagrass in our study. Substantial nutrient leaching below the root zone during establishment, particularly for deeper sand-caps would have been very likely under the frequent irrigation regimes and low CEC of these sands. This along with the lower surface moisture may have contributed to delayed establishment of the deeper capping depths.

Treatment Effects on Percent Green Cover and Turf Quality

Surprisingly, irrigation frequency did not have a major influence on overall turf quality on either subsoil during this the study. However, turf performance in regards to turf quality and percent green cover throughout both seasons did perform differently as a result of subsoil used. For example, the 10 and 20 cm capping depths sustained higher turf quality and cover when grown on the clay loam subsoil as compared to the fine sandy loam treatments. For example, the clay loam based plots never fell below the minimum acceptable visual quality rating of 5, nor did they fall below 50 percent green cover. Conversely, the 20 cm sand-cap on fine sandy loam did fall below the acceptable visual quality rating of 5 and below 50 percent green cover during the dry summer months. Collectively, these results emphasize the importance of the underlying subsoil physical characteristics on performance of the overlying sand-capping layer. The data also demonstrate that turf quality and performance could negatively be affected if an improper capping depth, whether too shallow or too deep, is chosen. Whether these relationships might change over time as organic matter accumulates to higher levels within the sand-cap layer is a question that can only be answered through longer-term testing. Infiltration rates can be reduced and higher water contents can develop as organic matter increases at the surface of turfgrass systems (Carrow, 1998). If organic matter accumulation increases to 5 % or more by weight, water-filled porosity increases with the loss of air-filled porosity (O'Brien and Hartwiger, 2003). Anaerobic conditions can arises near the root zone surface in this scenario.

Subsoil Sodium Adsorption Ratio (SAR) and Root Development

Adequate rooting, not only in the sand-cap but also in the subsoil, is important for turfgrass vigor and survival. In this study, total root length and root mass increased in the sand-cap as capping depth increased, however total root length and root mass decreased in the subsoil as capping depth increased. Total root length and root mass were also higher in the clay loam subsoil compared to sandy loam subsoil. Long-term maintenance of root development into the subsoil in sand-capped systems is an important consideration that should not be overlooked, especially during water restriction/drought periods and where high levels of sodium are present in irrigation water. Restricted rooting is a possibility that could develop as the underlying subsoil degrades and seals off due to high levels of sodium from irrigation. Major permeability issues can arise over time in fine texted soils when SAR values exceed 9 (USGA, 1994). Restricted rooting has also been shown to affect the ability of turf to withstand and recover from drought (Stienke et al., 20011 and 20013). Stienke et al. (2005) reported that following a 60-day drought period no warm-season turfgrass species survived on soil atop an impermeable plastic sheet, while all species survived where deep roots extended into subsoil (Stienke et al., 2011). Short-term drought stress in fairways has become a reality in recent years, as golf courses are forced to comply with water allocation reductions imposed by municipalities or water purveyors during periods of water shortage (Stienke et al., 2013).

Thatch Development and Hydrophobicity

Limiting the development of organic matter has always been an important cultural practice in turfgrass systems. Organic matter has a higher likelihood of accumulating on tee boxes and fairways compared to golf course greens due to the higher mowing heights and less frequent thatch removal programs (White, 2013). Other factors such as fertility rates, pH, temperature, and water quality affect organic matter development and can cause turgrass roots to decrease as organic matter increases (O'Brien and Hartwiger, 2003). Our research found that organic matter increased by 2% in all treatments over one season in this study. Surprisingly organic matter accumulation did not differ between the 5, 10, and 20 cm capping depth treatments. These data emphasize that for sand-capped systems, secondary cultural practices such as vertical mowing, topdressing, and aerating will likely be an extremely important component of a long-term maintenance program that should not be overlooked.

Hydrophobicity is another potential issue of concern within sand-based turfgrass systems. Areas on the deeper capping depths of 10 cm and 20 cm developed hydrophobic areas, in the upper 1.3 cm of the soil, and fell within the WDPT Class 2 (strongly water repellent) (Dekker el at, 2009). However, the shallower caps of 5 cm and the topdressing treatments showed no signs of hydrophobicity. The particle size of the sand will have a significant influence on the development of hydrophobicity in the soil, and studies have shown a coarse sand (0.5 to 2.0 mm) is more prone to develop hydrophobicity than finer-textured soils. This is primarily due to the extreme wetting-drying cycles that will increase the development of hydrophobic conditions (Karnok and Beall, 1995).

Summary and Conclusions

As the demand for improved turf performance and quality on large playing surfaces such as golf course fairways and athletic fields continues to increase, the construction method of sand-capping is gaining popularity. Thus, it has become increasingly important to examine how sand-capping depths and subsoil combinations affect the overall health and performance of turfgrass systems. Our results indicate the underlying subsoil will influence the ideal capping depth layer. No adverse effects were created with a shallower capping depth layer of 10 cm, and data suggest this shallower capping depth layer may be more appropriate, especially on the sandy loam subsoil to maintain more consistent turf quality throughout the season. A deep and extensive root system is a key factor in maintaining good turf quality and drought tolerance in turfgrass. Our results show that a deeper sand-cap layer significantly decreased this desired root development into the subsoil, and as SAR continues to increase in the subsoil over time, a restricted layer could form forcing roots to be concentrated in the above sand-cap layer. During drought and water restricted periods, this could negatively impact the ability of the turf to survive and recover. Furthermore, cultural practices and proper management of sand-capped systems must not be overlooked. The accumulation of organic matter over time created challenges of hydrophobic areas to form, especially on the deeper capping depths. Sand-capping has many benefits to better improve the playing conditions of golf courses and athletic fields, however it must be applied properly to avoid management and playing condition issues.

CHAPTER III

EVALUATION OF TEMPORAL AND SPATIAL DYNAMICS OF WATER MOVEMENT IN SAND-CAPPING SYSTEMS

Overview

In the recent years, sand-capping fairways and athletic fields have become common in both new construction and renovation projects. Ideally, sand might be placed atop a constructed drainage layer that allows rapid lateral movement of excess water to drain lines, as typical in putting green construction. However, sand-capping without a drainage layer offers a lower-cost option that is gaining popularity. While the dynamics of water movement in fields constructed with a drainage layer beneath the sand root zone has been well studied, it has not been intensely studied in fields capped with sand directly over soil.

The objectives of this study were to evaluate temporal and spatial dynamics of water movement in sand-capped fields, and to demonstrate how these dynamics vary from those in a field constructed with a gravel drainage layer. A field study was conducted in 2015 and 2016 at the Texas A&M Turfgrass Ecology Field Laboratory in College Station, TX. Measurements of water content and matric water potential were made after irrigation of 1m by 1m sand root zone plots constructed with and without a gravel drainage layer. The results demonstrated that there are appreciable differences in water movement in the sand root zones of fields constructed without a drainage layer compared to those constructed with a drainage layer.

Introduction

The USGA Section first published recommendations for constructing a putting green in 1960 (USGA Green Section, 1960). Since then, the USGA putting green construction method has undergone several revisions, the latest being in 2004 (USGA Green Section, 2004). This construction method consists of a installing a sand-based root zone mixture directly over a gravel layer. The gravel layer allows excess storm and irrigation water that flows through the sand to move laterally to drain lines. The gravel also serves to restrict the amount of water not under positive pressure from leaving the root zone.

Sand-capping of fairways is becoming a common management practice on golf courses. The construction of a sand-capped fairway generally involves first removing and stockpiling any topsoil for use elsewhere on the golf course. The fairways are then shaped and rough-graded using the subsoil. Subsurface drains are often installed at suitable intervals to help remove excess water. Then, the entire fairway is covered with a layer of sand (Thomas, 2014). The thickness of the sand layer is often based on anecdotal evidence from other courses that have been capped. The optimal thickness is not well studied, but likely is dependent on the physical properties of the sand to be used and the hydraulic properties of the subsoil. Due to cost, architects and owners often specify minimum capping depths and feather out the sand-cap near fairway edges. These thin areas of sand create challenging issues to produce consistent moisture levels and turf quality across the entire fairway. Regular topdressing to build up a sand-cap layer also provides alternative means for improving turfgrass systems. Kowalewski (2010) determined as much as 0.85 cm of sand could be applied per topdressing application to help build up a sand-cap layer. However, this process could take many years before adequate drainage and improved turfgrass systems are achieved.

Because sand caps systems are placed directly atop fine-textured soils rather than gravel, using recommendations for construction developed by the USGA (USGA, 2004) for construction of a putting green doesn't make much sense. In an USGA-design green water in the sand at the bottom of the root zone is limited in the rate, and thus the practical amount, that can drain out into the gravel when the water is not under positive pressure. The limit is determined by the unsaturated hydraulic properties of the gravel. Sand can remain saturated when not under positive pressure (i.e., when under negative water potential). Sands used in USGA-design putting greens typically remain near saturation until the water potential declines to values below -0.1 to -0.15 m water. When placed atop gravel water potential in the sand at the gravel interface declines to <0 m. McInnes and Thomas (2011) found water potentials at the sand-gravel interface to be between -0.05 and -0.09 m. Thus, some depth of sand closest to the gravel remains saturated after drainage following irrigation or rainfall. The lower the water potential at the interface – the less water in the root zone above. Water in a sand cap atop a fine textured soil likely will behave differently that water in the sand of a putting green because the fine soils can transmit appreciably more water at lower water potentials than can gravel. While drainage out of a USGA root zone into gravel declines to negligible amounts after a few hours, drainage out of a sand cap likely continues for a much longer time and at a rate determined by the pores size distribution and pore connectivity of the underlying soil (i.e., by its near saturated hydraulic conductivity).

Sand-capped fairways have many advantages including both improved playability and maintenance. The playing surface is improved to be more consistent, firm and smooth if sand-capped. The amount of interruption for the golf course after heavy rains can be reduced because of its drainage improvements. The maintenance is made easier among the fairways because of the consistency among the sand, which ensures the same drainage ability and characteristics (Robichaud and Banfield, 2006). Ultimately, to achieve a balance of air to water-filled porosity in the sand-cap layer, the ideal depth will depend on the physical characteristics of the sand, as well as the physical properties of the underlying subsoil.

The objectives of this study were to evaluate temporal and spatial dynamics of water movement in sand-capped fields, and to demonstrate how these dynamics vary from those in a field constructed with a drainage layer.

Materials and Methods

Research Site and Plot Construction

This research was conducted at the Texas A&M Turfgrass Field Laboratory, College Station, TX from August 2014 to October 2016. A 0.2 ha strip of sand-capped plots was constructed along a contour of a north-to-south running 0.01 to 0.02 m/m slope. The strip contained plots constructed atop two different soil surfaces, hereafter called subsoils. Properties of the subsoils were determined by a commercial lab using ASTM F1632-03 Method A (ASTM, 2010). Half of the strip was atop a Boonville fine sandy loam (fine, smectitic, thermic Ruptic-vertic Albaqualf) containing 15% clay, 20% silt, and 65% sand (mass basis). On the other half of the facility, the native Boonville soil was excavated to a depth of 30 cm and replaced with a locally sourced clay loam soil containing 38% clay, 35% silt, and 27% sand (mass basis). The resulting surfaces were laser graded to produce a 0.015 m/m east-to-west slope across the facility to facilitate drainage to ditches at the perimeter.

Atop each of the two subsoils (studies), irrigation frequency (main plots) and sand-cap treatments (sub-plots) were arranged in a split-plot design, with 3 replicate plots per treatment. Irrigation frequency treatments were the same total weekly irrigation supplied at either 1 or 2 times per week. All plots received irrigation volumes of 0.6 times reference evapotranspiration (ET_o) that was based on 40-year historical weather data for the location obtained through the Texas ET Network (texaset.tamu.edu). Rainfall amounts were recorded using a rain gauge, and used to adjust irrigation amounts accordingly (Table 2.1). The irrigation water used was the local municipal potable water source, which originates from deep aquifers and is of marginal agronomic quality, due to high levels of sodium bicarbonates (pH 8.1, SAR_{adj} = 23).

A locally sourced, medium-coarse textured sand was used to produce the sand-cap treatment plots, which were constructed to depths of either 0 cm (topdressed to a depth of 2.54 cm per year), 5 cm (shallow), 10 cm (medium), 20 cm (deep). Forms were used to achieve the desired depth, and a mechanical tamper was then used to firm and compact sand to prevent settling during establishment. A moisture barrier (CSP

Outdoors, Shreveport, LA) was then installed around all borders of each plot to a depth of 45 cm to prevent lateral movement of water between adjacent plots.

Sand-Capping Material

A Particle size analysis and physical measurement report of the capping sand was obtained by using the ASTM F1632-Method A and the ASTM Test Method F1815 by a USGA-accredited laboratory (Thomas Turf Services, Inc., College Station, TX). Based on those results, a moisture release curve relating sand water content to water potential was developed for the sand-capping material.

Volumetric Water Content

Soil volumetric water content within plots were monitored using 30-cm long TDR probes (Campbell Sci., Logan, UT) placed horizontally at various depths to determine spatial and temporal dynamics of water following irrigation and rainfall events. Two TDR probes were placed at a 5-cm depth in the 10-cm capping depth on both the 1x and 2x/wk irrigation frequency treatments, and two TDR probes were placed at a 5-cm and 15-cm depth on the 20-cm capping depth treatments on both the 1x and 2x/wk irrigation frequency treatments.

Water Potential and the Sand-Soil Interface

Plots constructed as 1 m by 1 m raised beds, independent of the larger plots describe above, were built and capped with 15 cm sand. Plots were constructed atop three subsurfaces: a sandy loam subsoil, a clay loam subsoil, and a gravel layer (10 cm to mimic the USGA putting green construction). Matric water potential sensors (a.k.a., tensiometers) were constructed from gas dispersion tubes with 25 to 50 micron pore size

(Ace Glass Inc., Vineland, NJ), low-pressure electronic sensors (26PC Series, Honeywell, Morris Plains, NJ), and a rigid delrin acetal resin tube (McMaster-Carr, Douglas, GA). These devices were used to measure the temporal dynamics of water potential at the bottom of the sand-cap after irrigation. Data were collected using a CR3000 datalogger (Campbell Sci., Logan, UT). Each plot was watered to saturation and allowed to drain while the matric water potential was recorded.

Results

Physical Properties of the Sand-capping Mixture

The particle size distribution of the sand had a wider range of particle diameters compared to a typical USGA construction mix (Figure 3.1). Because of the wider range in particle sizes the sand packed to a higher bulk density that typical of USGA-recommended sand for golf greens (1.85 g/cm^3 compared to typically ~1.6 g/cm^3) and a lower saturated hydraulic conductivity (32 cm/h compared to typically > 75 cm/h) (Table 3.1). The capping sand had very little silt or clay and chemical analysis determined the material had a neutral pH (Table 3.2). Twenty-five percent of the capping sand was gravel (Table 3.3 and Figure 3.1). The USGA recommends <30 g/kg (<3%) gravel for sand used in putting greens.

Table 3.1. Physical properties of the sand-capping material.

	Sat. Hydraulic Conductivity	Water Holding*	Bulk Density	Particle Density	Porosity		
					Total	Water-Filled	Air-Filled
	--cm/h--	--m^3/m^3--	--g/cm^3--	--g/cm^3--	--m^3/m^3--	--m^3/m^3--	--m^3/m^3--
Capping Sand at 40 cm Tension		0.062	1.85	2.65	0.302	0.115	0.187
Capping Sand at 30 cm Tension		0.073	1.85	2.65	0.302	0.135	0.167
Capping Sand at 20 cm Tension		0.125	1.85	2.65	0.302	0.231	0.071
Capping Sand at 10 cm Tension		0.136	1.85	2.65	0.302	0.252	0.05
Capping Sand at Saturation	32.3	0.145	1.85	2.65	0.302	0.268	0.034

*Water holding capacity of the sand-capping material from 0 to 40 cm of tension.
Core samples compacted using 21 drops of a 2.22 kg hammer at a height of 30.5 cm.
Particle density measured using ASTM D5550 Method C-2.

Table 3.2. Particle size analysis report for texture and chemical analysis of the sand-capping material.

	Texture			Chemical Analysis			
	Sand	Silt	Clay	pH	EC -- dS m^{-1}--	Extraction Method	Acid Reaction --1 M HCl--
U.S. Sieve No.	270 to 10	< 270					
Particle Diameter (mm)	.05 to 2.0	.002 to .05	<.002				
	------------g/kg------------						
Capping Sand	715	23	17	7	0.06	1 to 1	Severe
Duplicate	710	24	16				

Table 3.3. Sieve analysis of the sand in capping material (40 g/kg was silt and clay <0.05 mm).

	Gravel	Very Coarse	Coarse	Medium	Fine	Very Fine
U.S. Sieve No.	10	18	35	60	100	270
Particle Diameter (mm)	>2.0	1.0-2.0	0.50-1.0	0.25-0.50	0.15-0.25	0.15-0.05
	Retained on Sieve (g/kg)					
Capping Sand	245	147	163	269	106	30
Duplicate	250	144	157	273	109	27

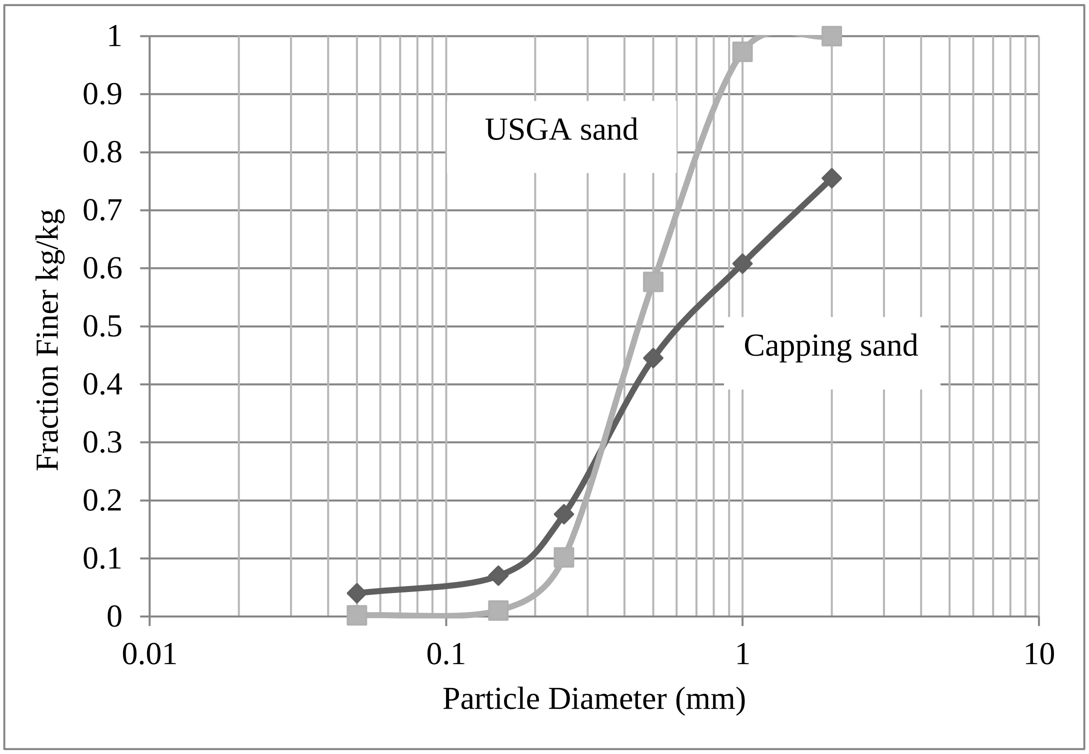

Figure 3.1. Fraction finer than a given diameter for a typical USGA root zone mixture and for the capping sand.

Moisture Release Curve

A moisture release curve is the relationship between the matric water potential and the water content of a porous material. That curve for the capping sand showed that the sand is composed of about 1/3 pore space and 2/3 solids on a volume basis and that the sand begins to desaturate at about -0.1 m matric water potential, it has lost half its water content by about -0.2 m, and it has lost 2/3 of its water by -0.3 m (Figure 3.2). Water content may also be called water-filled porosity. Air-filled porosity is the difference between total porosity and water filled porosity. Moisture release curves are used to determine the suitability of a sand for a USGA-design green. An equal balance of water to air-filled porosity in upper root zone is desired for vigorous growth of turfgrass. If the matric water potential at the bottom of the sand cap were 0 m, the ideal cap depth for our sand-capping material would be 22 cm, however, matric water potential is not likely to remain near 0 m long after irrigation or rainfall. As matric water potential decreases with drainage out of the sand cap, an estimate of the ideal cap depth, based on equal air and water-filled porosities in the upper root zone, would be less.

The greater the depth of a sand-cap the greater the water storage capacity will be and likely less runoff will be found during intense precipitation. In this study, the 20 cm capping depth was able to store up to twice as much water compared to the 10 cm capping depth treatment, depending on tension at the sand-soil interface (Figure 3.3).

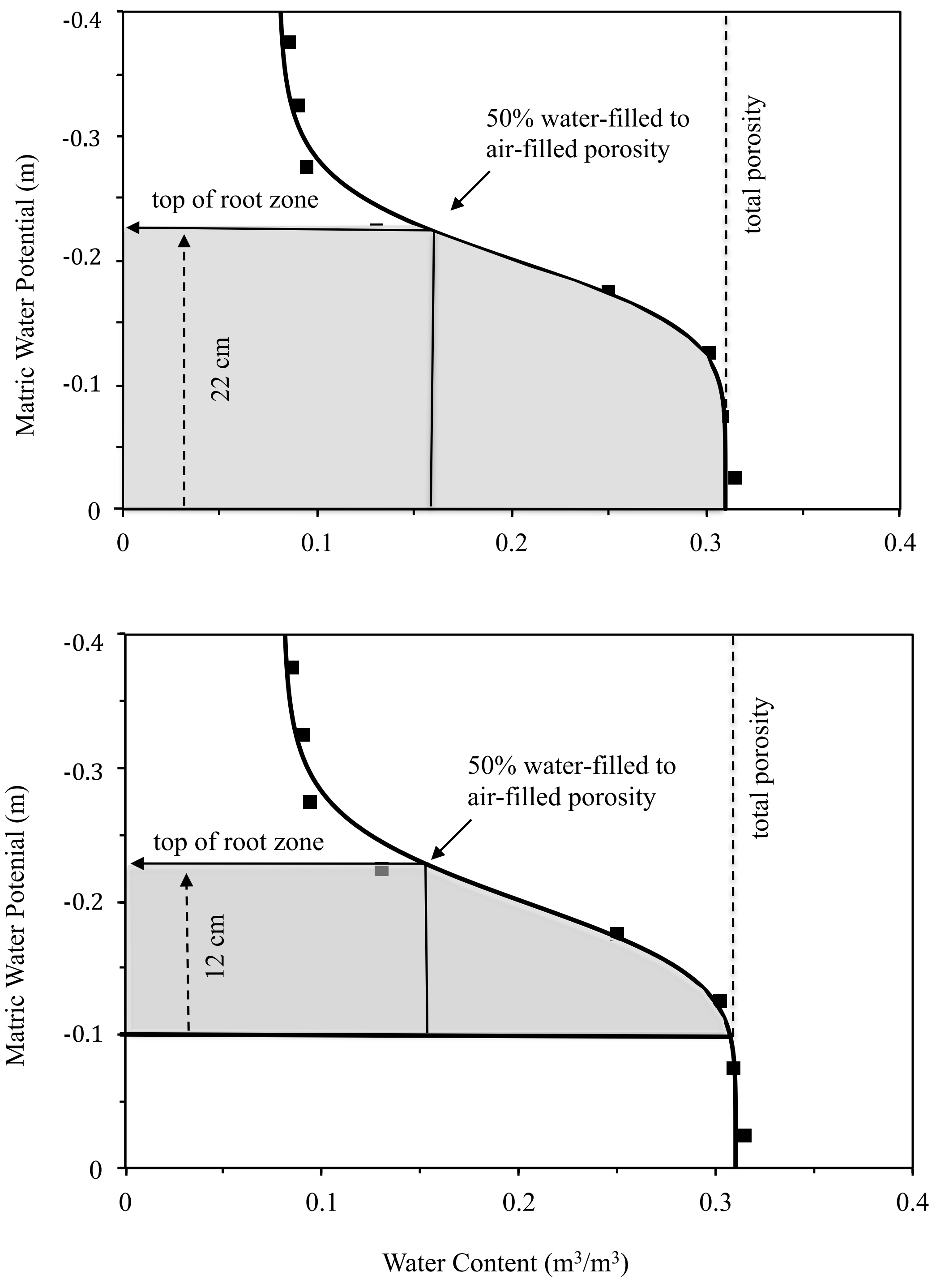

Figure 3.2 Moisture release curve depicting the relationship of matric water potential and water content for the sand-capping root zone mixture.

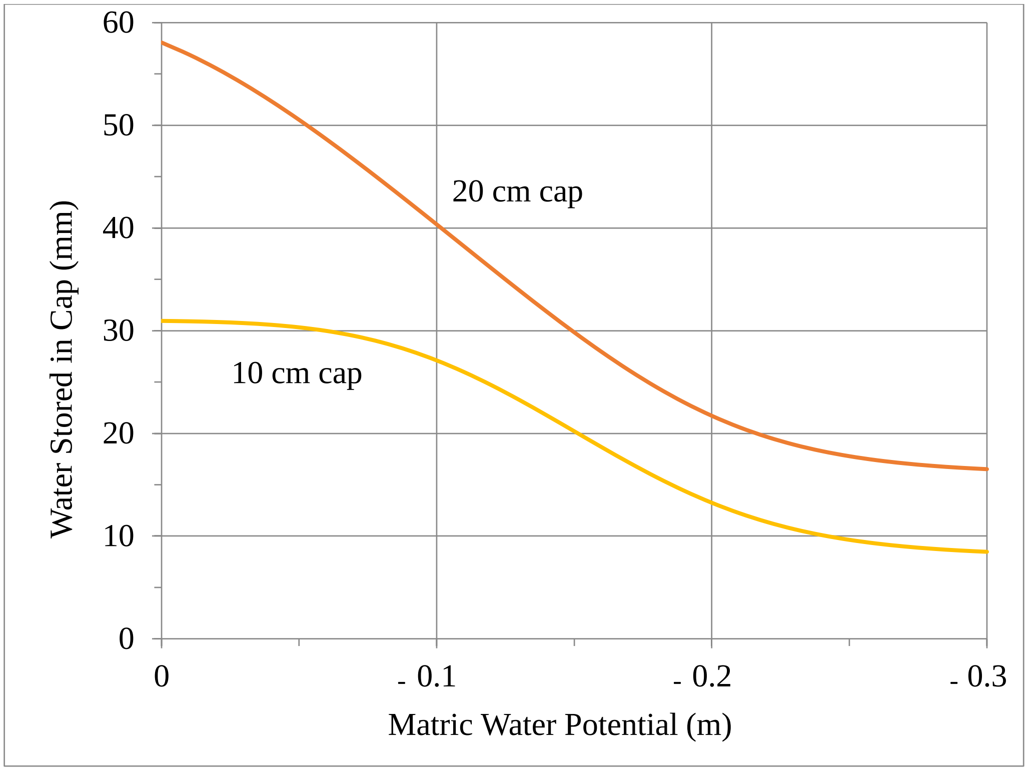

Figure 3.3. Graphic representation of the relationship of the amount of water stored in the sand-cap by the matric water potential at the bottom of the sand-cap root zone.

Temporal Dynamics of Matric Water Potential at the Sand-Subsurface Interface

A matric water potential sensor know as a tensiometer is a water-filled instrument that exchanges water with the soil through a porous cup. It can be used to record positive or negative water potentials. Positive potentials are associated with standing water where water will drain freely into a large void given an avenue and gravity. When water potential is negative (matric water potential) water does not drain freely into a large void, unless it creeps along the walls.

After plots were irrigated to saturation, matric water potential was monitored at the interface of the sand-cap and the subsurface. The lowest matric water potential developed when the capping sand was atop the sandy loam (Figure 3.4). The temporal trend in matric water potential at the sand-clay interface was intermediate to that at the sand-sandy loam interface and the sand-gravel interface. Due to the lack of an impermeable barrier around the box frames, water under positive water potential was able to run out from beneath the frame sides. The transition from positive to negative water potential could have taken longer had the plot been larger; depending on how much irrigation was supplied. However, results due show how the different underlying treatments will affect water dynamics at the bottom of a sand root zone.

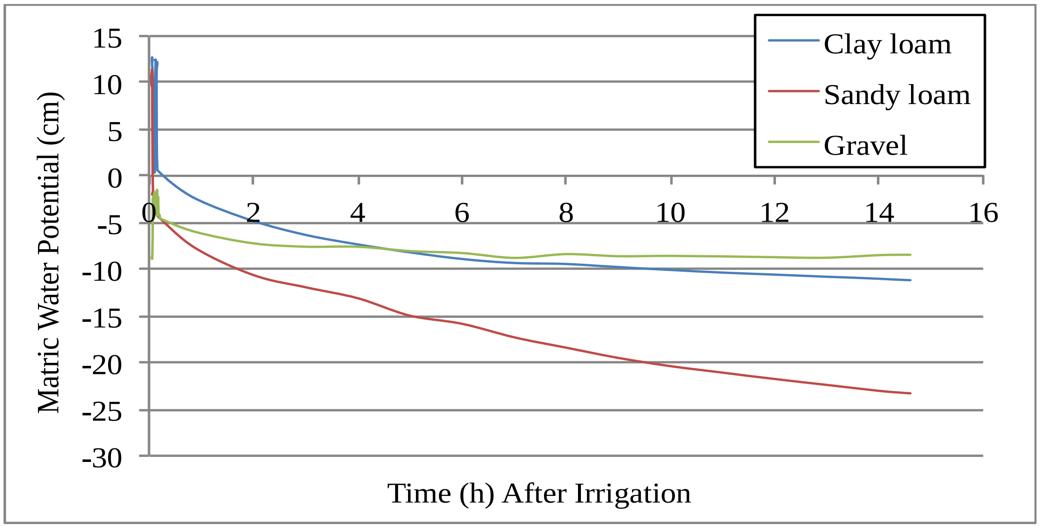

Figure 3.4 Matric water potential at the bottom of the sand-cap root zone as affected by time after irrigation on the sandy loam, clay loam, and gravel layer treatments.

Volumetric Water Content

On the large plots used to investigate capping depth, irrigation was supplied at amounts corresponding to 0.6 times ET_o, based on 40-year historical weather data, at frequencies of either 1x or 2x per week. The large spikes in water content (Figure 3.5, 3.6, 3.7, and 3.8) indicate when plots where irrigated and the downward stair steps on the line indicate daytime (riser) and nighttime (tread) periods. Water content was depleted after 72 hours on the 1x per week irrigation treatments, whereas the 2x per week irrigation treatments helped to replenish the sand (Figure 3.5). As expected from the moisture release curve and gravity, water content remained higher for the majority of the period between irrigation cycles at the 15 cm depth compared to the shallower (surface) 5 cm depth (Figure 3.6 and 3.8). The sand-cap above the clay loam subsoil on average had a higher water content and was able to retain more moisture within the sand-cap compared to the sandy loam subsoil.

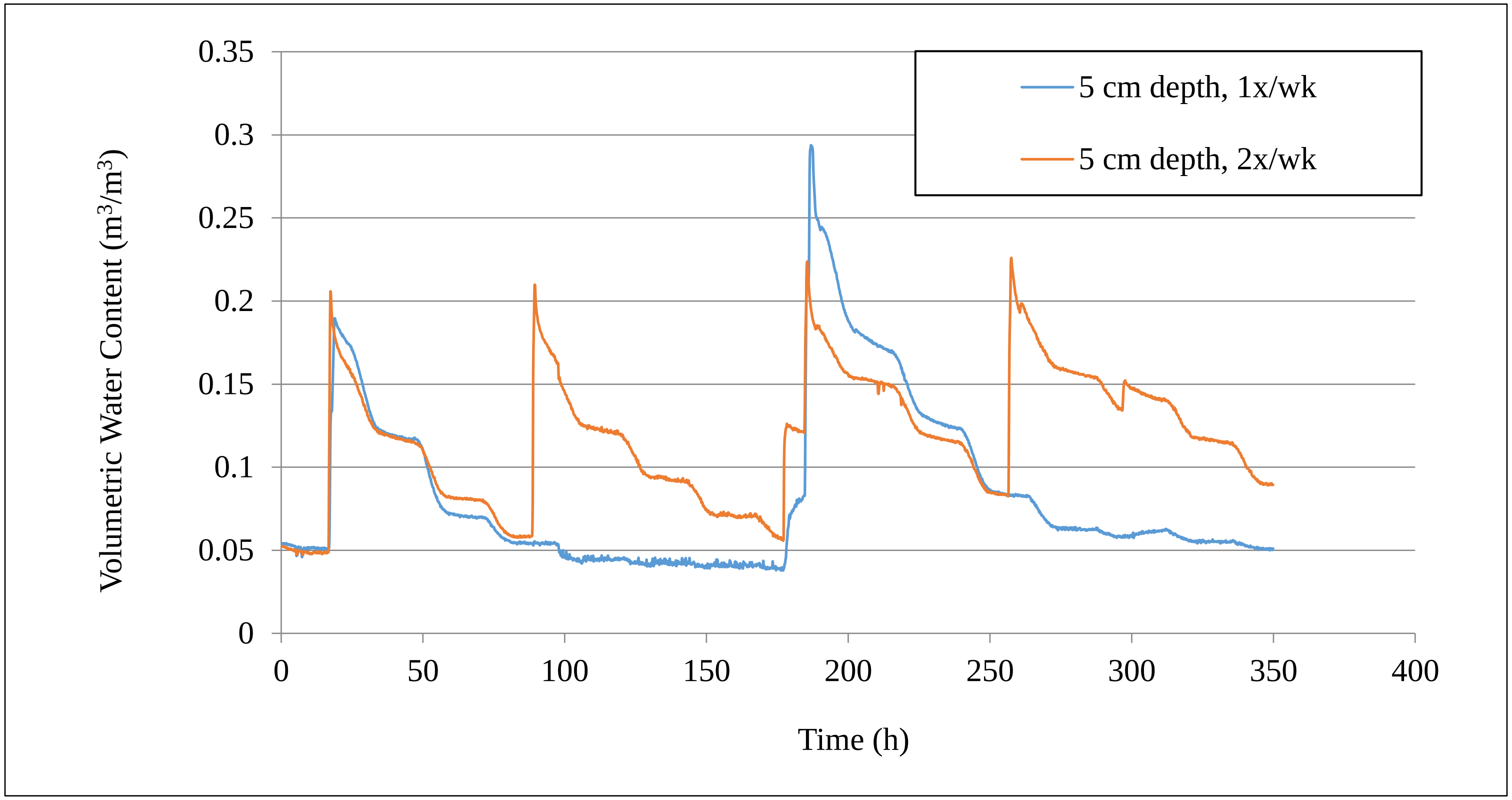

Figure 3.5. Volumetric water content in the 10 cm sand-cap on the sandy loam subsoil as affected by time after irrigation. TDR moisture probes were placed at a 5 cm depth in the 1x and 2x/wk irrigation treatments. A total amount of 25.5 mm of water was applied to the 1x and 2x/wk irrigation treatments.

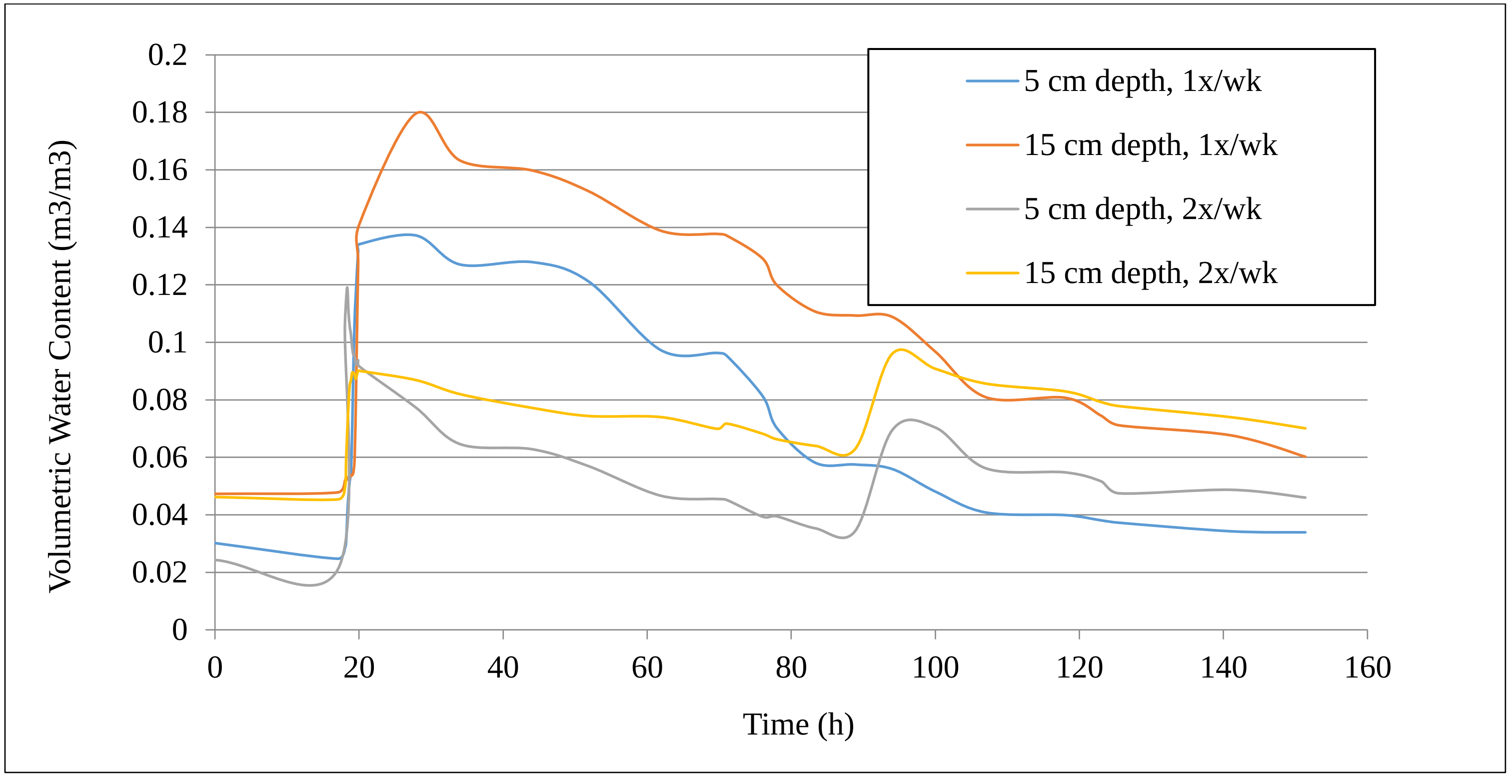

Figure 3.6. Volumetric water content in the 20 cm sand-cap on the sandy loam subsoil as affected by time after irrigation. TDR moisture probes were placed at a 5 and 15 cm depth in the 1x and 2x/wk irrigation treatments. A total amount of 25.5 mm of water was applied to the 1x and 2x/wk irrigation treatments.

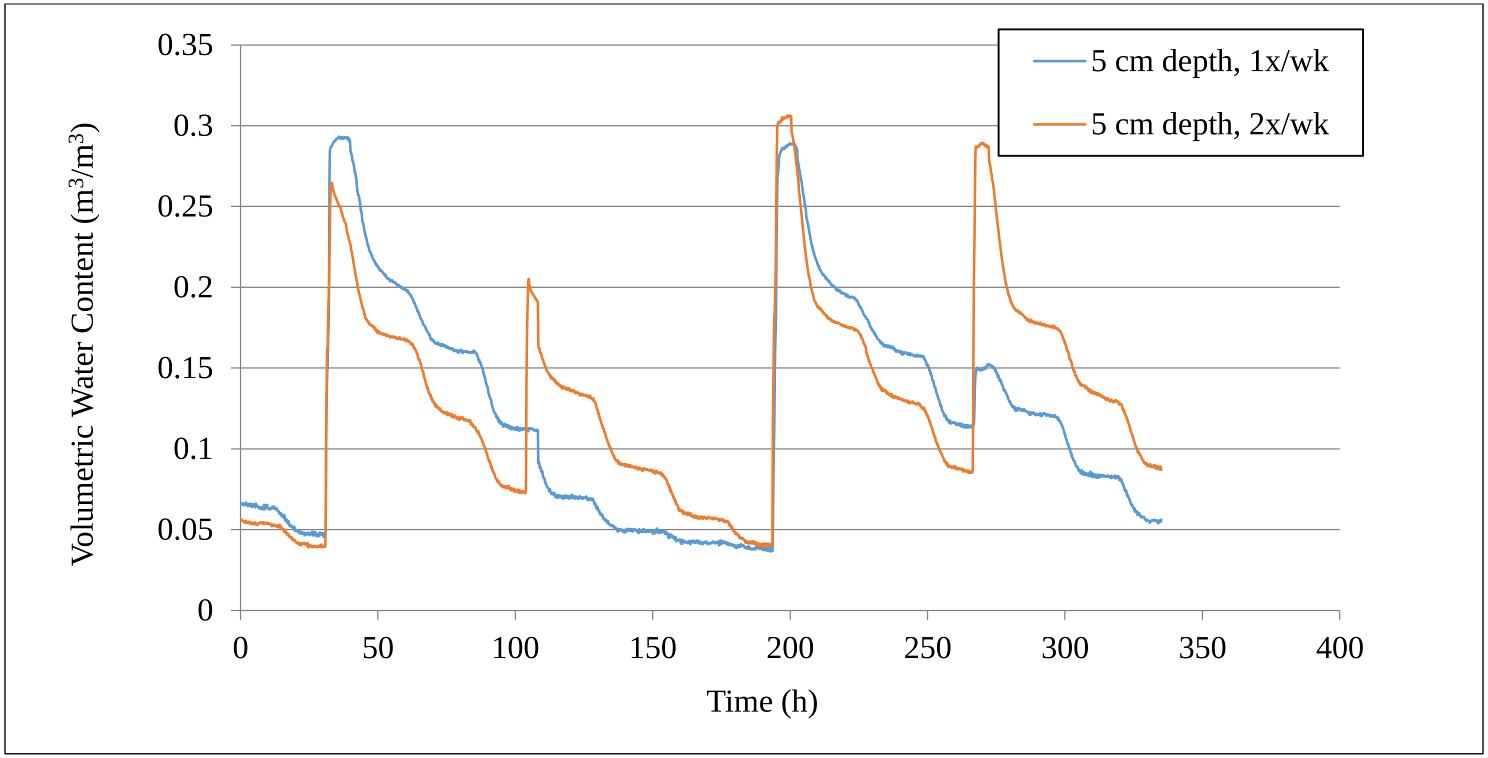

Figure 3.7. Volumetric water content in the 10 cm sand-cap on the clay loam subsoil as affected by time after irrigation. TDR moisture probes were placed at a 5 cm depth in the 1x and 2x/wk irrigation treatments. A total amount of 25.5 mm of water was applied to the 1x and 2x/wk irrigation treatments.

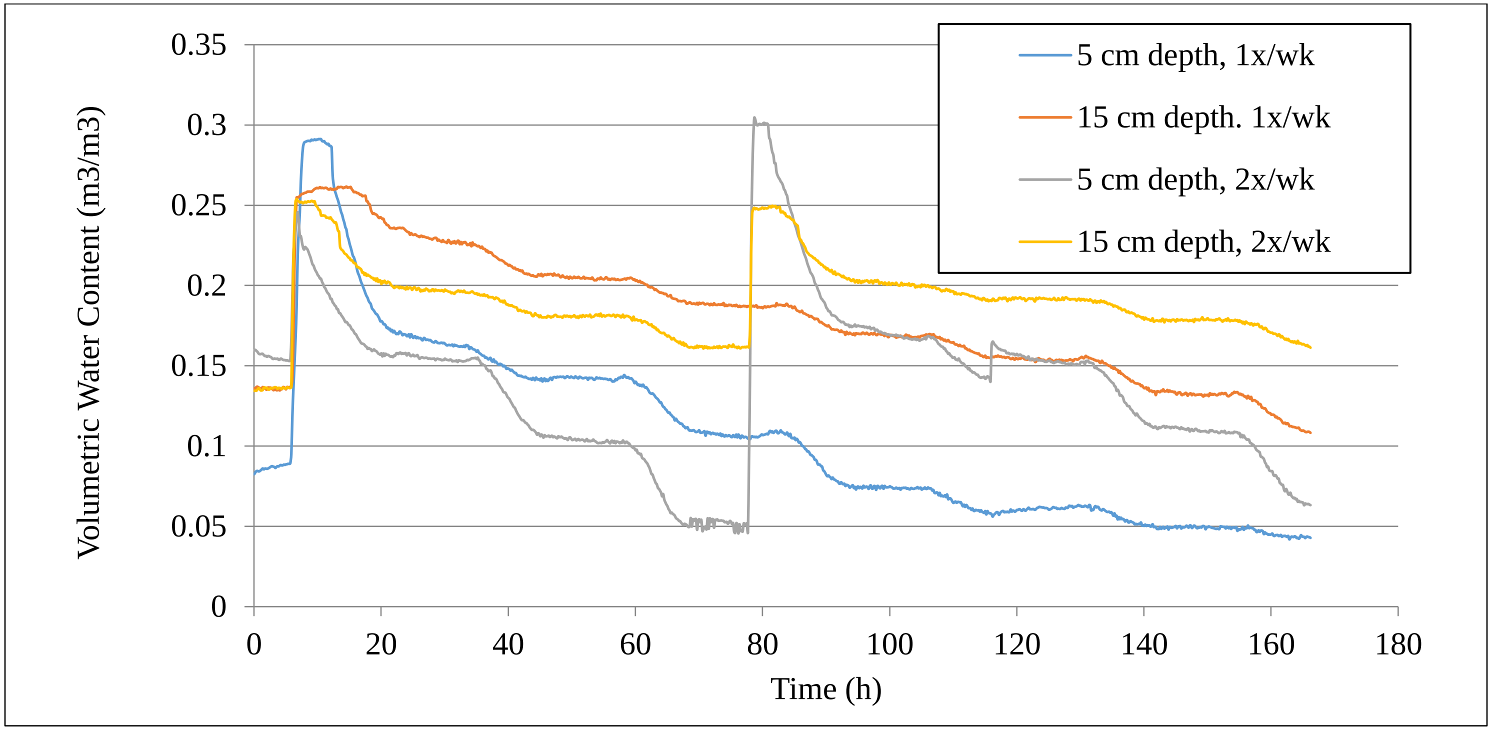

Figure 3.8. Volumetric water content in the 20 cm sand-cap on the clay loam subsoil as affected by time after irrigation. TDR moisture probes were placed at a 5 and 15 cm depth in the 1x and 2x/wk irrigation treatments. A total amount of 25.5 mm of water was applied to the 1x and 2x/wk irrigation treatments.

Discussion

Sand-Capping Properties

Due to the major construction and renovation cost associated with sand-capping, many golf courses are using a cheaper grade sand than recommended for a putting green construction using the USGA design. The capping sand used for this project was very coarse and has a wider range of particle diameter than used for a USGA putting green construction. One major difference between the two sand materials was the USGA recommends no more than 10% of total particles should fall in the range of very course and fine gravel (USGA, 2004), however 38% of the capping sand fell in this range. The high bulk density of the capping sand may provide some advantages by creating a firmer surface, which can be great for playability.

Continuing, in both sand-capped and USGA construction-design systems there will be a loss of moisture in sand layer during unsaturated periods by evapotranspiration, however in sand-capped systems the underlying soil also has the ability to pull/wick water from the above sand layer. This creates the scenario where moisture content throughout the sand layer in sand-capped systems tend to dry out faster compared to the USGA construction-design, however turfgrass roots are not restricted in sand-capped systems and can grow further down into the subsoil to access water. This can be vital during periods of drought for the survival of the turfgrass.

Tensiometers were utilized to measure how matric water potential developed at the interface of the sand-cap and underlying subsoil after irrigation, and how it compared to that developed on the USGA design. Likely due to the low unsaturated conductivity in the gravel layer, only -5 cm of matric water potential developed at the interface. In sand-capped systems, a lower matric water potential was able to develop at the interface, likely due to the greater unsaturated hydraulic conductivity of the subsoils compared to the gravel. The sandy loam treatment allowed a lower matric water potential to develop compared to the clay loam treatment, likely due to its greater unsaturated hydraulic conductivity at the matric water potentials that developed. The lower matric water potentials at the interface shows that more water was being pulled/wicked out of the sand-cap on the sandy loam subsoil compared to the clay loam subsoil or the gravel. Water contents measured with the TDR probes support this finding. Less water was being retained in the sand-cap on the sandy loam subsoil compared the clay loam subsoil. This was especially evident where volumetric water content at 15-cm depth in a 20 cm sand-cap was less on the sandy loam treatments compared to the clay loam treatments.

Summary and Conclusions

Sand-capping can have many advantages over native soil construction. One of those advantages is the ability to capture and hold more water, which reduces runoff. A deeper capping depth may be more appropriate in areas that experience high amounts of precipitation. However, to provide optimal turfgrass growing and playing conditions for golf courses and athletic fields, recommended sand-capping depths have to be considered differently than the current recommendation developed for the USGA-design putting green. A challenge of sand-capping systems is how the different physical properties of various subsoils will affect the ideal capping layer above. We observed lower matric water potential and less moisture in the sand-cap atop a sandy loam subsoil compared to sand atop clay loam subsoil, 6 to 8 % less moisture content. This shows that the underlying subsoil will have a major effect on the sand-cap's ability to retain moisture, which plays a factor in recommending an appropriate capping depth layer. Depending on your environmental conditions, we conclude a shallower capping depth of 10 cm may be more appropriate over the deeper 20 cm capping depth. The 10 cm capping depth provides enough surface drainage during precipitation events and outperformed the deeper capping depth of 20 cm during drought stressed periods. Though simple in concept that sand-capping helps in managing turf quality and performance, determining the ideal recommendation of sand for each scenario is quite complex due to the varying properties of the sand to subsoil combinations and environmental conditions.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Sand-capping is used to improve playing conditions on golf courses and athletic facilities, especially when the soil is degraded or there is a need to rely on poor-quality irrigation water. Since there was scant research on the effects of sand-capping depth and its interactions with the type of subsoil and irrigation water quality, we conducted a two-year study to evaluate the effects of these variables on turfgrass establishment and performance. In this study, we evaluated the establishment of Tifway bermudagrass on plots capped with different depths of sand and also monitored temporal changes in water content and chemical properties of the sand and soil. Soil water content near the surface was an important factor affecting the establishment of turf on the plots. Our findings demonstrated that deeper sand caps, 20 cm compared to 10 and less cm, require more frequent irrigation to establish turfgrass at a favorable rate. A capping depth of 10 cm allowed establishment at rates and quality similar to shallower depths. Our data suggests that 10 cm is a safe depth to recommend.

Results showed consistently higher turf quality and performance on the sand-caps above the clay loam subsoil compared to the sandy loam subsoil. Water content data showed that more water was retained in the sand-cap above the clay loam subsoil compared to the sandy loam subsoil. This information is useful for turf managers to help them provide better turf quality and playing surfaces dependent on the underlying subsoil.

Irrigation water applied to plots had a SAR_{adj} of 23, and we observed over the two-year study the development of increasing SAR in the underlying subsoils. Facilities increasingly relying on irrigation water with a high concentration of sodium will see an increase development of SAR in the underlying subsoil over time, and this may cause the subsoil to degrade and seal off. Adequate rooting into the underlying subsoil will become very important during periods of prolong drought for the survival of the turfgrass species.

This research could positively impact the golf industry by leading to development of science-based sand-capping recommendations for golf courses. Our research has shown recommending a proper sand layer for sand-capping systems will differ greatly from other construction methods, such as the USGA-design construction.

Future projects should focus on cultural management practices that address problems that might arise in sand-capped fields, such water restriction periods and proper management to reduce SAR accumulation in the subsoil.

REFERENCES

ASTM International. 2010. Standard test method for particle size analysis and sand shape grading of golf course putting green and sports field rootzone mixes. Designation: F1632-03.

Bisdom, E. B. A., L. W. Dekker, and J. F. T. Schoute. 1993. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure, Geoderma, vol. 56, pg. 105–118.

Carrow, R. N. 1998. Organic matter dynamics in the surface zone of a USGA green: practices to alleviate problems. *USGA* 1998 Turfgrass and Environmental Research Summary. USGA, Far Hills, N.J.

Carrow, R. N., and R. R. Duncan. 1998. Salt-affected turfgrass sites: Assessment and Management. Ann Arbor Press. Chelsea, MI.

Carrow, R. N., M. Huck, and R. R. Duncan. 2000. Leaching for salinity management on turfgrass sites. USGA Green Section Nov/Dec.

Dekker, L. W., and C. J. Ritsema. 1994. How water moves in a water repellent sandy soil: 1. Potential and actual water repellency, Water Resource. Res., 30, 2507–2517.

Dekker, L.W., C.J. Ritsema, K. Oostindie, D. Moore, and J.G. Wesseling. 2009. Methods for determining soil water repellency on field-moist samples. Water Resource. Res. 45:W00D33.

GCSSA. 2015 Water use and conservation practices on U.S. golf courses. Golf course environmental profile. Phase II, volume I. Environmental Institute for Golf.

Harivandi, M.A. 2004. Evaluating recycled waters for golf course irrigation. USGA Green Section Record Nov/Dec: 25–29.

Haydu, J. J., A. W. Hodges, and C. R. Hall. 2008. Estimating the economic impact of the U.S. golf course industry: challenges and solutions. HortScience 43(3):759-763.

Huck M., R. N. Carrow, and R. R. Duncan. 2000. Effluent water: nightmare or dream come true? USGA Green Section March/April.

Karcher, D.E. and M.D. Richardson. 2003. Quantifying turfgrass color using digital image analysis. Crop Sci. 43:943-951.

Karcher, D.E. and M.D. Richardson. 2005. Batch analysis of digital images to evaluate turfgrass characteristics. Crop Sci. 45:1536-1539.

Karnok, K., and M. Beall. 1995. Localized dry spots caused by hydrophobic soil: what have we learned? Golf Course Manage.

Kowalewski, A.R., J.R. Crum, and J.N. Rogers, III. 2010. Built-up sand-capped athletic field system. Available at http://turf.msu.edu/assets/ArticlePDFs/Built-Up-Sand-Capped-System.pdf.

McInnes K. J. and Thomas J.C. 2011. Water storage in putting greens constructed with United States golf association and airfield systems designs. Crop Science, Vol. 51, May-June.

McIntyre, K. and B. Jakobsen. 1993. Design, construction and maintenance of sand-based facilities using the principal of the perched water table.

O'Brien, P., and C. Hartwiger. 2003. Aeration and topdressing for the 21st century. *USGA Green Section Record.* 41 (2): 1-7.

Robichaud, S. and A. Banfield. 2006. Creating an improved golf experience. GreenMaster. Vol. 41. Issue 1.

Rodriguez I. R., Grady L. Miller, L. B. Mcarty. 2001. Bermudagrass establishment on high sand-content soil using various N-P-K Ratios. HortScience 37(1): 208-209.

Sayre, G. D. 1991. Fairway topdressing. Golf Course Management. 59(7): 30-38.

Stienke, K., D. Chalmers, J. Thomas, and R. White. 2011. Bermudagrass and buffalograss drought response and recovery at two soil depths. Crop Science 51:1215-1223.

Stienke, K., D. Chalmers, R. White, C. Fontainer, J. Thomas, and B. Wherley. 2013. Lateral spread of three warm-season turfgrass species as affected by prior summer water stress at two root zone depths. HortScience 48: 790-795.

Thomas, J. 2014. Personal communication.

United States Golf Association. 1960. Specification for a method of putting green construction. USGA Green Section Staff. USGA Journal and Turf Management: Sept. 1960.

United States Golf Association. 1994. *Wastewater reuse for golf course irrigation.* Lewis Publishers, Chelsea, MI.

United States Golf Association. 2004. USGA recommendations for a method of putting green construction. pg 1-10.USGA.org. Turfgrass and Environmental Research.

White, B. 2013. Sand capping solves everything . . . or does it? USGA Green Section Record 51(17).